ANL-ART-177

Development of Diffusion-type Hydrogen Meters for Steam Generator Leak Detection System of Sodium-cooled Fast Reactors

Nuclear Science and Engineering Division

ANL-ART-177
Rev: 0

Development of Diffusion-type Hydrogen Meters for Steam Generator Leak Detection System of Sodium-cooled Fast Reactors

Prepared by
Hual-Te Chien, Thomas W. Elmer, William P. Lawrence, and Edward O'Hare

Nuclear Science and Engineering Division
Argonne National Laboratory

September 2019

This page intentionally left blank.

EXECUTIVE SUMMARY

The goal of this project is to develop and demonstrate diffusion-type hydrogen meters (DTHMs) for hydrogen concentration in cover gas or in molten sodium. Prompt detection of steam-to-sodium leaks of a sodium-heated steam generator (SHSG) is one of the most important economic and safety issues to be addressed in designing and operating a sodium-cooled fast reactor (SFR). A water-to-sodium leak causes a violent exothermic sodium-water reaction (SWR) resulting in local temperature rise (>1,200°C) and produces hydrogen gas and highly corrosive chemicals. The SWR often induces self-enlargement (self-wastage) of the leak and rapid propagation of wastage to adjacent tubes, leading to secondary or multiple tube failures. If it is unmitigated, the hydrogen gas formation could cause a pressure increase in the reactor and may cause a SHSG blowdown, and ultimately result in shutdown of the reactor. In addition, if their effects are unmitigated, the highly corrosive chemicals formed could lead to and accelerate the corrosion problems of the SHSG and sodium piping.

Among all the steam generator leak detection techniques, DTHMs are highly sensitive and effective in detecting small leaks to prevent further tube failure due to wastage propagation. Argonne conducted studies to identify the design requirements and specifications and designs of DTHMs, including cover-gas hydrogen meter (CGHM) and in-sodium hydrogen meter (ISHM), to be integrated into the steam generator leak detection system of a SFR. The R&D efforts during FY19 have been focused on (a) creep-collapse tests of different designs of nickel membrane probes, (b) performance evaluation of CGHM prototypes, (c) fabrication of ISHM prototypes, and (d) construction of experimental apparatus for in-sodium performance evaluation of ISHM prototypes.

A creep-collapse test apparatus was designed and constructed. Ten straight nickel membrane probes and two ribbed nickel membrane probes were fabricated tested at temperature 600°C under pressure from 100 to 1,000 psig. It appeared that the new bullet cap and collar designs and ribbed membranes prolong the membrane surviving time. It is inconclusive if the membranes' strength weakening is caused by the welding process, imperfection of the membranes, grain size/boundary at high temperature, or for some other reason.

A test apparatus for performance evaluation of CGHM prototypes was designed and constructed. Two CGHM prototypes have been fabricated and tested. The test results clearly show that the dynamic mode reaches an equilibrium state much faster than the equilibrium mode but with much smaller magnitude. Both modes demonstrated hydrogen detection sensitivity down to 2 ppm or less in argon cover gas as required by the specification. Under the dynamic mode, the CGHM prototype has a response time around 1 sec. The equilibrium shows better consistency but with much longer response time. Both operation modes, if calibrated, can provide direct measurements of hydrogen concentration or pressure.

The compact ISHM is designed for fast response, reduced cost, simplicity, sensitivity, and seismic ruggedness. It has no sodium pump, valves, or flowmeter and is mechanically supported by the sodium line to which it is closely coupled. The fabrication of the first compact ISHM is completed and the second one is in progress. The design specifications and operating procedures of the proposed compact diffusion-type ISHM were identified. The fabrication of an in-sodium test apparatus and its integration with the USV facility have been in progress. Performance evaluation of the compact ISHM prototypes will be conducted after the construction and integration are completed. Compact ISHM is expected to detect promptly the hydrogen concentration in sodium down to less than 1-ppm ranges.

To enhance the strength and life expectancy of nickel membranes, some processes, such as surface analysis, heat-treatment, better machining methods, or alternative fabrication technique (3D printing), need to be further investigated. Section 10 provides the future plan for the development and performance evaluation of both CGHM and ISHM.

This page intentionally left blank.

Acknowledgments

The work reported here was sponsored by the U.S. Department of Energy (DOE), Office of Nuclear Energy's Advanced Reactor Technologies (ART) program. The DTHM team would like to thank Mr. Grandy for his guidance and technical direction throughout the course of this effort.

A special acknowledgement of thanks goes to Mr. Thomas Sowinski, Fast Reactor Program Manager for the DOE-NE ART program and to Dr. Robert Hill, the National Technical Director for Fast Reactors for the DOE-NE ART program for their consistent support of the Advanced Concepts work.

Argonne is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC under contract DE-AC02-06CH11357.

This page intentionally left blank.

Acronyms and Abbreviations

3D	Three Dimensions
A/D	Analog/Digital
C&D	Control and Display
ANL	Argonne National Laboratory
ANSI	American National Standards Institute
ART	Advanced Reactor Technology
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
CGHM	Cover-Gas Hydrogen Meter
CHMLD	Compact Hydrogen Meter
DAQ	Data Acquisition
DOE	U.S. Department of Energy
DOE-NE	Office of Nuclear Energy in the Department of Energy
DTHM	Diffusion-Type Hydrogen Meter
EB	Electron Beam
EBR-II	Experimental Breeder Reactor II
FRFHMLD	Fast Response Freezable HMLD
FBR	Fast Breeder Reactor
FY	Fiscal Year
HMLD	Hydrogen Meter Leak Detector
IAEA	International Atomic Energy Agency
I&C	Instrumentation and Control
ID	Inner Diameter
IHTS	Intermediate Heat Transport System
IHX	Intermediate Heat Exchanger
ISHM	In-Sodium Hydrogen Meter
NI	National Instruments™
OD	Outer Diameter
SFR	Sodium-Cooled Fast Reactor
SG	Steam Generator
SHSG	Sodium-heated Steam Generator
SGLDS	Steam Generator Leak Detection System
SS	Stainless Steel
SWR	Sodium-Water Reaction
SWRPRS	Sodium Water Reaction Pressure Relief System
TC	Thermocouple
FFTF	Fast Flux Test Facility
USV	Under-sodium Viewing

This page intentionally left blank.

Contents

Figures

Tables

This page intentionally left blank.

1 INTRODUCTION

Prompt detection of water-to-sodium leaks in a sodium-heated steam generator (SHSG) of a sodium-cooled fast reactor (SFR) is one of the most important economic and safety issues to be addressed in designing and operating an SFR. A water-to-sodium leak causes a violent exothermic sodium-water reaction (SWR) resulting in local temperature rise (>1,200°C) and produces hydrogen gas and highly corrosive chemicals. The SWR often induces self-enlargement (self-wastage) of the leak and rapid propagation of wastage to adjacent tubes, leading to secondary or multiple tube failures. If it is unmitigated, the hydrogen gas formation could cause a pressure increase in the intermediate heat exchanger (IHX) or the intermediate heat transport system (IHTS) and may potentially cause IHX tubing rupture or IHTS piping failure. A rapid SG tubing failure may cause a SG blowdown and ultimately result in shutdown of the reactor. In addition, if their effects are unmitigated, the highly corrosive chemicals formed could lead to and accelerate corrosion problems of SG and IHX/IHTS structures. From the viewpoint of reactor safety, the primary consideration in relation to SG leak is to maintain the integrity of the primary coolant boundary. SFRs typically incorporate a Sodium Water Reaction Pressure Relief System (SWRPRS) to prevent damage to the IHX or IHTS from pressurization and vent SWR products that might otherwise ultimately result in a lengthy shutdown of the reactor. The secondary safety consideration and an economic aspect are to effectively and rapidly detect any leaks to isolate the affected SG while maintain power on the grid. To limit the effects of SWR that include the potential for propagation of failures to other SG tubes, early leak detection and rapid steam generator blowdown capabilities are effective ways to mitigate the consequences of sodium-water reactions. Early leak detection and rapid steam generator blowdown capabilities are effective ways to mitigate the consequences of sodium-water reaction (SWR). While the SWRPRS is a passive system, an alarm from the SGLDS would be used to isolate the steam and feedwater lines connected to the SG, depressurize/vent the SG, and backfill the SG tubes with inert nitrogen gas.

The leak-rate range of interest spans several orders of magnitude and so a variety of sensing systems have been developed since no single instrument works well over the entire range. There is likewise a wide range of sensor response times. An effective Steam Generator Leak Detection System (SGLDS) is often incorporated and may require various types of monitors, sensors, and subsystems placed at various locations in the SG system to detect water and steam leakage with proper match of measurement sensitivity, range, and response time. Recently Argonne surveyed and assessed various types of those sensors that are suitable for SG leak detection in SFRs [1,2]. In general, most SFR designs use hydrogen monitors to detect small water/steam leaks, rupture discs that are part of the SWRPRS to protect the IHX/IHTS from large leaks, and active or passive acoustic leak detection systems for continuous and instantaneous detection of small to intermediate leaks. For intermediate to large leaks, several conventional types of sensors can also be used for leak detection, such as a pressure gauge and a level sensor to monitor the pressure change in the SG cover-gas and the sodium level in the IHTS, respectively. These reference reports also cover a detailed survey on various empirical and computational models that describe and simulate the sodium-water reaction phenomena and wastage/leak propagation. Optimal sensor designs were also presented based on their sensitivity and reliability. One of the applicable leak detection techniques is to detect hydrogen concentration in sodium or hydrogen pressure in cover gas by using diffusion-type hydrogen meters (DTHMs). The hydrogen detectors are highly sensitive sensors but relatively poor in response time depending on where the detectors are installed. They are effective in detecting small leaks to prevent further tube failure due to wastage propagation.

The objective of this project is to develop DTHMs to be integrated into the SGLDS of a SFR. The FY19 workscope includes three major tasks: 1) creep-collapse test of nickel membranes with different wall thicknesses and designs, 2) development and performance evaluation of CGHM, and 3) development of ISHM. This report documents the progress of the development and performance evaluation of DTHMs prototypes. Section 2 describes the FY19 workscope and Section 3 reports the classification of water/steam leaks generally accepted by IAEA and the leak growth mechanism and the associated damages/risks for each class of leak. Section 4 describes the SWR at different operation temperatures and stages. Section 5 reports the working principle and the design analysis of DTHM, including relationships of detection sensitivity with the ionization gauge sensitivity in detecting the pressure variation on the vacuum side of the membrane. Two types of DTHM, in-cover hydrogen meter (CGHM) and in-sodium hydrogen meter (ISHM), are recommended for *in-situ* real-time hydrogen monitoring.

Section 6 documents the designs and fabrications of a creep-collapse test apparatus as well as straight and ribbed nickel membrane probes. This section also reports and analyzes the results of creep-collapse test of ten straight and two ribbed membrane probes. Two additional test apparatuses were also constructed to study flow-induced vibration of ribbed nickel membranes in water with different flowrates and strain/displacement of ribbed nickel membranes perturbed by a shaker with different vibration intensities. The test results are documented and discussed in this section.

Section 7 reports the progress of the development and performance evaluation of diffusion-type CGHM. A CGHM consists of four major modules, a nickel membrane probe, a vacuum manifold and hydrogen measuring system, a hydrogen injection system, and a standpipe unit. A test apparatus was designed and constructed for the performance evaluation of CGHM prototypes. The apparatus consists of a pressure test vessel, a hydrogen injection assembly, ion pump and gauge, and gas mass-flow controller. Two prototypes have been fabricated and tested under dynamic and equilibrium modes to determine hydrogen concentration. Test results demonstrate that the two prototypes fulfill the design requirements and achieve a detection sensitivity of hydrogen concentration of 2 ppm.

Section 8 presents the development of compact diffusion-type ISHM, which consists of five major modules: a compact nickel membrane probe assembly, a vacuum manifold and hydrogen measuring system, a sodium hydrogen injection assembly, a leak analyzer, and a control and display unit. One prototype has been fabricated and the fabrication of the second one is in progress. This section also documents the design specifications and operating procedures of the proposed compact diffusion-type ISHM. The Argonne under-sodium viewing (USV) facility will be used for in-sodium performance evaluation of ISHM prototypes. An in-sodium test apparatus of ISHM prototypes was designed. The fabrication of the test apparatus and its integration with the USV facility has been in progress and are discussed in this section.

Section 9 discusses the findings and conclusions of the creep-collapse tests of different membrane probes and the performance evaluation of the two CGHM prototypes. Different machining and fabrication techniques of nickel membranes are suggested for the improvements of strength and life expectancy of nickel membranes. Section 10 provides a future plan for the development of both CGHM and ISHM. References cited in this report are listed after the future plan.

2 WORKSCOPE

FY19 workscope includes the following three major tasks:

Creep-collapse test of nickel membrane probes

- *Creep-collapse tests of straight and ribbed nickel membrane probes*

  Argonne has constructed a creep-collapse experiment apparatus, consisting a high-pressure test vessel (~300psig) and furnace (~600°C), and gas mixing module, for laboratory pilot testing. Argonne has completed different nickel membrane designs for CGHM and ISHM, respectively. Accordingly, Argonne will fabricate different nickel membrane probes, including straight and ribbed tublar membranes, and then conduct creep-collapse tests at different pressures (100 - 1,000 psig) at 560°C (1,040°F).

- *Strength validation of ribbed membrane in flow*

  Argonne will construct an in-flow test apparatus and then conduct tests to validate strength of ribbed membrane probes under different flow rates and flow-induced vibrations.

- *Strain/displacement tests of ribbed membrane*

  Argonne will construct a strain/displacement test apparatus and then conduct tests to measure strain/displacement of ribbed membrane probes under different vibrations generated by a shaker. The associated strain/displacement will be measured simultaneously by a laser vibrometer as well as the two strain gauges mounted on the end of the probe.

Development of diffusion-type cover-gas hydrogen meter (CGHM) prototypes

Argonne has designed a diffusion-type CGHM and two prototypes have been fabricated and tested. Argonne has also constructed an experiment apparatus for laboratory pilot testing of the CGHM prototypes. The apparatus consists of a pressure test vessel (<30psig), a hydrogen injection system, and a gas mass-flow controller. Different hydrogen/argon gas mixtures will be injected into the argon cover gas to determine the meter performance. The performance evaluation covers the following three major subtasks:

  - Determine the sensitivity, response time, and reproducibility,
  - Determine the calibration requirements and procedure,
  - Determine the optimal meter operating conditions.

Development of Diffusion-type in-sodium hydrogen meter (ISHM) prototypes

- *Fabrication of diffusion-type ISHM prototypes*

  Argonne has completed the ISHM design and two in-sodium DTHM prototypes will be fabricated for laboratory pilot testing and performance evaluation.

- *Design and construction of in-sodium test apparatus*

  Argonne will design and construct an in-sodium test apparatus for laboratory pilot testing of ISHM prototypes. The test apparatus with a sodium hydroxide injector will be integrated onto the under-sodium viewing (USV) facility.

- *Laboratory pilot testing of ISHM prototypes*

  After the completion of the in-sodium test apparatus, Argonne will conduct laboratory pilot testing of the ISHM prototypes by either injecting sodium hydroxide into sodium or changing the temperature of the cold trap to produce different hydrogen dissolutions in sodium to determine the meter performance.

3 STEAM-TO-SODIUM LEAK CLASSIFICATION AND PHENOMENA

Sodium-water reaction (SWR) results in local temperature rise to a peak temperature of approximately 1,200–1,400°C and produces highly corrosive chemicals such as NaOH and Na_2O. The SWR will also generate hydrogen gas that may result in pressure increase in the system and potentially cause tubing rupture. Table 1 provides a generally accepted classification for water/steam leaks and dominant damages and threats [4]. The leak growth mechanism and the associated risks for each class of leak are as follows:

Micro Leaks (< 0.1g/sec) – A micro leak is often developed from an inter-granular crack in a defected weld or a fatigue crack in a tube wall. The corrosive reaction products often remain in place and plug the leak.

The leak may stay plugged for a long time, several days or weeks, but it may still be active as the accumulation of corrosion products continue to grow.

Small Leaks (1.0–10 g/sec) – A small leak often causes localized tube damage, a phenomenon termed self-wastage. The leak grows by a combination of corrosion and erosion. A small leak can also cause damage to adjacent tubes, a damage type called impingement wastage. The water jet from a small leak forms a turbulent under-sodium “flame”. The center of the flame is a core of un-reacted steam at a temperature of 300–500°C. This is surrounded by a reaction zone with temperatures in 1,200–1,400°C depending on the pressure. This flame may impinge on another tube, causing wastage by corrosion and erosion. Small leaks grow at an accelerating rate and eventually blow out instantaneously without any detectable warning. Conservatively, the upper leak rate limit was later reduced from 50 g/sec to 10 g/sec in 2012 [5].

Intermediate Leaks (10–2,000 g/sec) – When the leak rate rises into the intermediate range, the reaction flame becomes large and affects many other tubes. The flame interacts with the flowing sodium and the result is a chaotic turbulent interaction region characterized by widely fluctuating temperatures.

Large Leaks (> 2,000 g/sec) – A large leak may cause a rapid pressure rise in the SG due to a large amount of hydrogen gas generated from SWR. It may in turn cause great damage to the components of the secondary cooling circuits. The damage timescale is in seconds.

Table 1: Classification of water/steam-to-sodium leaks in a steam generator

Leak Class	Leak Rate (g/sec)	Dominant Threat and Phenomena
Micro	< 0.1	Too small to be detected, Reaction products formed slowly, bubbling may occur, Defects tend to plug. No threat to other tubes.
Small	0.1 – 10*	Generating a corrosive sodium-water reaction jet, Damage to adjacent tubes – Impingement wastage.
Intermediate	10* – 2,000	Lower end – Damage to adjacent tubes by wastage, Higher end – Tube failure by overheating and pressurization due to H_2 production (single tube).
Large	> 2,000	Rapid pressurization due to hydrogen production (multiple tubes), Tube failure by overheating and overpressure, Potential explosion on top of the core cover.

*Leak rate was reduced from 50 g/s to 10 g/s in 2012 [5].

A slight modification to the leak classification and the associated damages was suggested in the steam generator safety system design of MONJU FBR [6]. The requirements proposed by IAEA on leak detection method are (a) the sensitivity of the order of a few g/s, (b) detection time on the order of a few seconds, and (c) the false alarm rate less than one in two years. Table 2 outlines the proposed sensor requirements for steam/water leak detection of SG [6,7].

Table 2: Steam/water leak detection requirements

Criterion	Definition	Unit	Measuring Tool
Measurement Ranges	0.045 – 10 1 – 1000 > 1000	ppm	ISHM CGHM Acoustic Detector
Resolution	<0.045	ppm	Hydrogen Meter
Sensitivity	100	ppb	ISHM
Response time	12	sec	Hydrogen Meter
Required Detection Times	2 15 2	h min min	Leak rate = 0.005 g/s Leak rate = 0.05 g/s Leak rate = 0.2 g/s
Operating Environment	Sodium T: >480 Cover-gas P: ~4.9	°C atm	

4 SODIUM-WATER REACTION (SWR)

If there is a leaking of high-pressure water or steam into low-pressure sodium flow channels, SWR occurs instantaneously. Equation 1 shows the main sodium and water reaction at 500°C:

$$2\ Na\ (l) + 2\ H_2O\ (l/g) \rightarrow 2\ NaOH\ (s/l) + H_2\ (g) + 324\ KJ/water\ mole \tag{1}$$

This complete, quasi-instantaneous and non-reversible reaction forms the colorless and strong basic solutions of sodium hydroxide (NaOH) and sodium hydride (NaH), and hydrogen gas (H_2). The reaction also releases a great amount of heat resulting in local temperature to rise up to a peak temperature of approximately 1,200–1,400°C.

Sodium oxide can be produced by a secondary reaction of sodium with sodium hydroxide as

$$2\ NaOH + 2\ Na \rightarrow 2\ Na_2O + H_2 \tag{2}$$

This reaction relies on the reduction of SWR product by sodium. However, this equilibrium reaction depends on sodium temperature, dissolved hydrogen, and hydrogen partial pressure equilibrium. The reversible exothermic chemical reactions are

$$NaOH + 2\ Na \Leftarrow 2\ 1 \Rightarrow [O_2^-]Na + [H^-]Na \Leftrightarrow Na_2O + NaH \tag{3}$$

Above about 300°C, with sodium in excess, hydroxide is decomposed in sodium oxide and hydride (reaction 1⇒). Above 410°C, reaction (⇐2) occurs only if hydrogen partial pressure reaches equilibrium in the cover gas. Otherwise, the decomposition of NaOH is total. The reaction rates depend on temperature. Liquid sodium may react with a rapid flow of hydrogen gas at 177°C to produce the ionic compound sodium hydride ($Na^+\ H^-$), which is a base and a reducing agent:

$$2\ Na + H_2 \Leftrightarrow 2\ NaH \tag{4}$$

The SWR produces highly corrosive chemicals, such as NaOH and NaH, and solid particulates of Na_2O. These chemical effects cause corrosion of tube and components due to oxides and cause stress corrosion cracking due to NaOH, and local erosion/corrosion due to propagation to surrounding structures. The reaction also generates hydrogen gas that may result in pressure increase in the IHX/IHST system and potentially compromise its integrity.

When sodium temperature is relatively low during reactor startup and low-power operation, hydrogen gas can reach the cover gas and thus online monitoring of hydrogen in cover gas can provide useful information about water/steam leakage. Based on the past survey, the diffusion type cover-gas hydrogen meter is the preferred choice [1,2]. In-sodium hydrogen meters, on the other hand, can monitor the hydrogen level in sodium but the required sensitivity (< 0.1 ppm) and reliability must take into account the background hydrogen level (typically > 100 ppb), noise fluctuation (3 to 6 ppb), and long-term electronic drift (~10 ppb).

5 DIFFUSION-TYPE HYDROGEN METERS (DTHM)

Depending on the required detection sensitivity and response, several different types of hydrogen monitoring techniques have been used to detect water/steam leaks. The DTHM is the selected design of both cover-gas and in-sodium applications to small detect water/steam leaks. Typically, a CGHM is installed in the expansion tank and an ISHM at the sodium outlet of each SG. Both meters will be used for *in-situ* real-time hydrogen monitoring, but will not be integrated into the reactor safety system.

5.1 Design of DTHM

The major components of a DTHM consist of:

- A nickel membrane probe,
- Heating device and temperature controller,
- A vacuum manifold with a roughing pump,
- An ion pump,
- An ionization gauge,
- An isolation valve between ion pump and ionization gauge, and
- *In-situ* meter calibration unit.

The nickel membrane probe consists of a thin nickel diffusion membrane that is connected to a vacuum manifold system operated with an ion pump. Detailed meter construction has slight variations between cover-gas and in-sodium hydrogen meters. Typically, the membrane has a cylindrical cross section as shown in Figure 1. The hydrogen flux diffusing through the membrane is measured by the ion pump current or by an ionization gauge. The sensitivity of these hydrogen meters (μamps/ppb H) is proportional to A/x, where A is the surface area of the membrane and x is the thickness of the membrane. The response time is directly proportional to x^2 and the sensor location from the leak. For example, a pure nickel tube of OD = 1.27 cm (0.5”), x = 14 mil (0.356 mm), and A = 45.2 cm^2 (7 in^2) will have a response time of 24 sec at the leak site, and a sensitivity of ~ 0.13 μamps/ppb H with a standard 8 liter/sec ion pump. For *in-situ* meter calibration, CGHM uses a hydrogen injection module and ISHM uses a sodium hydroxide injection assembly.

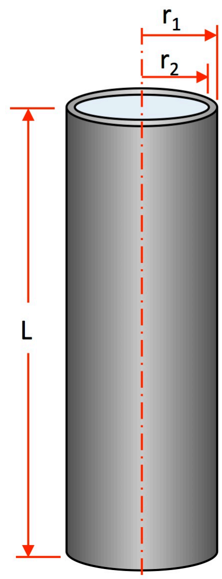


Figure 1. Cylindrical membrane tube.

5.2 Design Analysis of DTHM

In general, the ion pump current reflects the hydrogen flux diffusing through the nickel membrane and thus it gives a dynamic mode of hydrogen measurement. The ionization gauge also gives a measure of hydrogen pressure. However, if one isolates the ion pump, the ionization gauge gives an equilibrium mode measurement of hydrogen pressure, which represents the hydrogen partial pressure in the cover gas or the hydrogen concentration in sodium. Detection sensitivity of a DTHM is therefore determined by the gauge sensitivity in detecting the pressure variation on the vacuum side of the membrane. The pressure variation, dP/dt (torr/sec), depends on the amount of hydrogen gas flowing in the vacuum system per unit time, Q (torr-liters/sec), the pumping speed, S (liter/sec), and the outgassing from the wall and gauges. In general, the wall outgassing can be neglected in most cases, especially during the dynamic mode. The basic equation for pressure variation may be written as

$$dP/dt = (Q - P_{VC}S)/V, \tag{5}$$

where V (liters) is the volume of the vacuum system. Integrating Eq. (5) over time t, one obtains the vacuum side pressure variation for the dynamic operation, given in Eq. (6).

$$P(t_0 + \Delta t) = P(t_0)\, e^{-S\Delta t/V} + Q/S\,(1 - e^{-S\Delta t/V}) \tag{6}$$

When operating in the equilibrium mode ($S = 0$), Equation (6) reduces to

$$P(t_0 + \Delta t) = P(t_0) + Q\,\Delta t/V. \tag{7}$$

Hydrogen flux, J_X, through a semi-infinite metal plane due to the hydrogen concentration gradient, dC/dx, can be obtained from Fick's first law:

$$J_X = -D\, dC/dx = -D\,(C_2 - C_1)/x, \tag{8}$$

where D is the diffusion coefficient, C_1 and C_2 are hydrogen concentrations at the outer and inner surfaces of the membrane, and x is the membrane thickness. C_1 and C_2 can be related to the partial pressures, P_1 and P_2, of hydrogen on both sides of the membrane using Sievert's law:

$$J_X = - k_P (P_2^{1/2} - P_1^{1/2})/x, \tag{9}$$

where k_P is the permeability coefficient that is a function of temperature T and can be expressed as follows:

$$k_P = k_P^0 \exp(-E_P/RT), \tag{10}$$

where k_P^0 is the temperature independent permeability constant, E_P is the activation energy for permeation, and R is the gas constant. Table 3 lists permeability constants, k_p^0, of a few metals [8]. The permeability coefficient for hydrogen is the highest for palladium. However, Pd, Pt, and Cu are not considered as candidate materials because of their poor compatibility with sodium. Nickel is better than iron due to its easy workability, high resistance toward oxidation, and high sodium resistance.

Table 3: Permeability parameters for different membrane materials

Membrane Material	k_p^0 ($mol.cm^{-1}s^{-1}atm^{-1/2}$)	E_p (kJ/mol)
Pd	5.0746 x 10^{-6}	17.598
Pt	1.4513 x 10^{-6}	75.420
Cu	2.8467 x 10^{-7}	69.554
Fe	2.0172 x 10^{-7}	40.224
Ni	1.2994 x 10^{-6}	56.146

The hydrogen flux ($J_X = dn/dt$) across the cylindrical membrane tube is

$$\frac{dn}{dt} = 2\pi L k_P \left(P_1^{\frac{1}{2}} - P_2^{\frac{1}{2}}\right) / \int_{r_2}^{r_1} \frac{dr}{r}, \tag{11}$$

where P_2 is the hydrogen partial pressure inside the tube, an equilibrium pressure established by the vacuum system. Variation of P_2 over the time depends on the hydrogen flux and the vacuum pump speed. Since the pump speed is a constant specified by the ion pump. The variation of P_2 over a unit time interval can be given by

$$\frac{dP_2}{dt} = \frac{2k_P RT}{r_2^2 \ln\frac{r_1}{r_2}} \left(P_1^{\frac{1}{2}} - P_2^{\frac{1}{2}}\right), \tag{12}$$

where R is gas constant and T is the absolute temperature. The rate of pressure increase on the vacuum side of the hydrogen meter is proportional to the hydrogen pressure difference. Integrating Eq. (12) over P_2 from initial $P_2 = P_0$ to $P_2 = P_t$, the required time (t) can be calculated from

$$t = C\left[P_1^{\frac{1}{2}} \ln\frac{P_1^{\frac{1}{2}} - P_0^{\frac{1}{2}}}{P_1^{\frac{1}{2}} - P_t^{\frac{1}{2}}} - \left(P_t^{\frac{1}{2}} - P_0^{\frac{1}{2}}\right)\right], \tag{13}$$

where $C = (r_2^2 \ln r_1/r_2)/(k_p RT)$.

6 DESIGN AND CREEP-COLLAPSE TEST OF NICKEL MEMBRANES

This section documents different designs of nickel membranes for CGHM and ISHM based on the design specifications. Before fabrication of DTHM prototypes, creep-collapse tests of nickel membranes with different wall thicknesses and different designs were conducted to evaluate the maximum operation pressure of the nickel membranes and to determine the optimal thickness to be used for desirable diffusion time, i.e. the meter response time. The tests would also be able to estimate the life expectancy of the membranes.

6.1 Designs of Nickel Membranes

According to the operation conditions, including pressure, temperature, flowrate, and coolant media, the design specifications of different types of DTHM are varied. Based on the design specifications, different designs of nickel membrane for CGHM and ISHM were conducted. The tubular seamless nickel membrane is made of Nickel–201 (ASTM B-161), which is the material successfully used in hydrogen meters employed in EBR-II. Nickel–201 is a pure nickel (99%) with low carbon (< 0.02%), a preferred nickel for high temperature (> 320°C) applications.

6.1.1 Nickel Membrane of CGHM

Under normal operating conditions, the pressure of a typical expansion tank of SFR is ~1.5 atm (~22 psia). Based on the CGHM performance specifications, a nickel membrane should operate normally even if the pressure of the expansion tank reaches 17 atm (250 psia). The membrane of CGHM has a cylindrical cross section as shown in Figure 2. For fast diffusion rate, i.e. fast response time, and better membrane stiffness, nickel membrane probes with two different wall thicknesses, 10 and 14 mil, were selected for the evaluation of the maximum operation pressure of the membranes and the determination of the optimal thickness to be used for desirable meter response time.

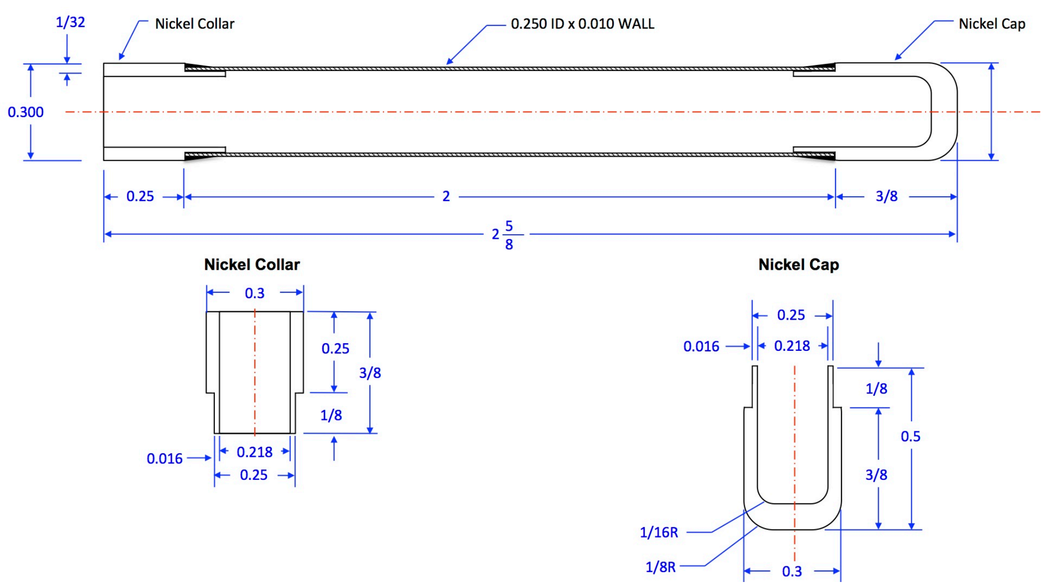


Figure 2. Revised design of nickel membrane.

Ten membrane probes have been fabricated for creep-collapse test. A SS union is used to connect a membrane probe to the test chamber, to provide a vacuum seal, and to allow quick removal of the probe from the chamber for probe inspection and replacement. Each membrane has a SS cap welded at one end and a SS tube at the other end. The SS tube is then welded to the inner side of the union. The outer side of the union was welded to another SS tube, which connects to a low-pressure manifold. Figure 3 shows the nickel membrane probes with wall thicknesses of 10 and 14 mil and a close view of membrane welded onto a SS tube.

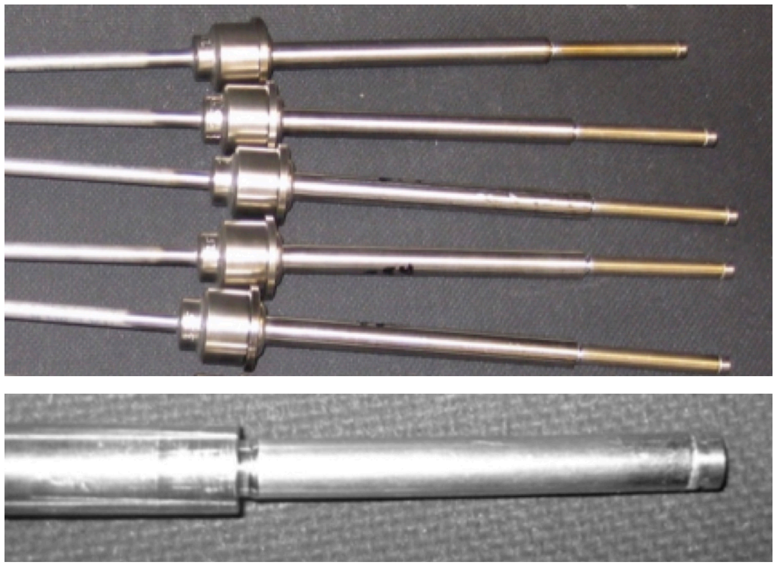


Figure 3. Nickel membrane probes for creep-collapse test.

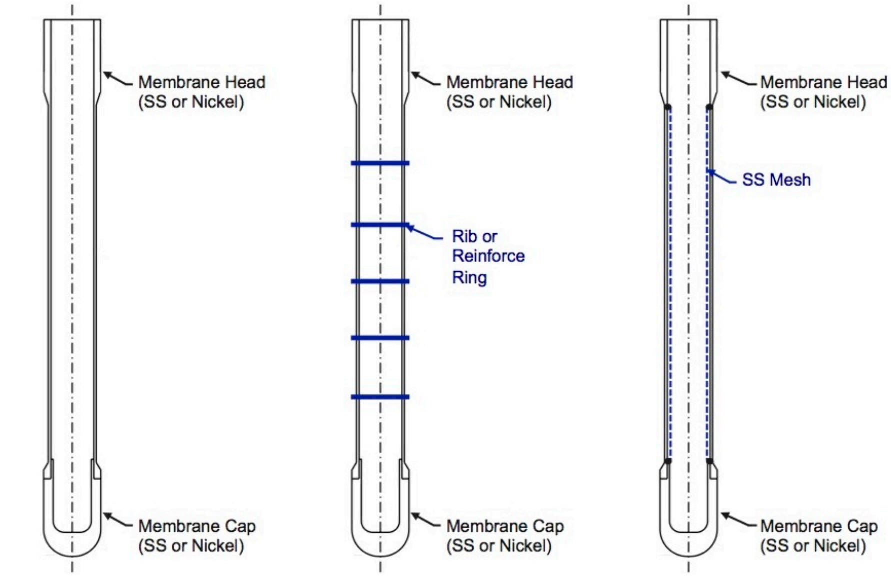
6.1.2 Ribbed Nickel Membranes of ISHM

The nickel membrane probe of ISHM consists of a membrane cap, a transition sleeve, and a tubular nickel membrane. The design of the tubular membrane may vary depending on the working environment. Since it is evacuated in use, the wall is under compression, and failure would be by collapse. Under higher pressure and sodium flow rate, an ISHM may require a thicker membrane, alternative membrane designs, or use different materials, such as a composite tube of nickel or 2.25Cr-1Mo steel. However, all these alternatives might change its hydrogen diffusion time, i.e. the detection time of the meter. Three typical designs of nickel membrane, shown in Figure 3, were proposed and evaluated before.

<u>*Plain membrane:*</u> Ni-membrane creep-collapse tests were conducted in the past and showed that at about 6.8 atm (100 psia) external pressure, the compressive hoop stress in the membrane is about 10 MPa (1,550 psi), which can be sustained by a plain 10-mil membrane, shown in Figure 4(a), which is sufficient for a CGHM.

<u>*Ribbed membrane*</u>: A ribbed membrane, shown in Figure 4(b), was designed to enhance its strength and still maintain minimal diffusion time. A ribbed membrane would use a thicker membrane tube that is machined down to the desired thickness with multiple ribs consisting of equal separation spacing along the length of the membrane. Machining the membrane is extremely challenging, for example, to keep a uniform membrane thickness down to 10 mil and surface quality (scale or defect free). Another alternative method is to weld or machine multiple SS or nickel reinforce rings on the outside of the membrane. The welding or machining quality and stress relieves also poses challenges.

<u>*Meshed membrane*</u>: To enhance strength and still maintain minimal diffusion time, a SS metal mesh tube with thicker thickness would be inserted inside the membrane. Figure 4(c) shows the design of Meshed membrane.



(a) (b) (c)

Figure 4. Three nickel membrane designs of ISHM: (a) plain, (b) ribbed, and (c) meshed.

The design of a ribbed membrane has been selected. The membrane is made of the same material (Nickel–201) and the same wall thickness (0.254 mm) as that of the CGHM developed. Figure 5 shows the design and photo of a ribbed nickel membrane probe. The probe is welded to a transition sleeve that leads to the inlet for the vacuum feedthrough and a cap is welded on the other end. For welding compatibility, the sleeve is a cold-drawn seamless tubing made of Nickel-Chromium-Iron Alloy ASTM B166 (UNS N06600) and is used to join the nickel membrane and the SS-304 vacuum feedthrough. Three weld-buttons were welded on the probe cap with equal spaces to guide the slide-fit during assembly and to prevent vibration while the ISHM is in operation. Before machining, the membrane has an OD of 15.875 mm (5/8 in.), ID of 12.7 mm (0.5 in.), and length of 95.25 mm (3.75 in.). Its wall thickness is milled down to 0.254 mm (10 mil) with five ribbed separated evenly (~12.5 mm) giving a total active surface of 30.53 cm^2 (4.73 in^2) for hydrogen diffusion and a volume of 9.69 cm^3 (0.59 in^3). It is recommended that, after machining and welding, the nickel membrane receives low carbon stress relief treatment at 400°C.

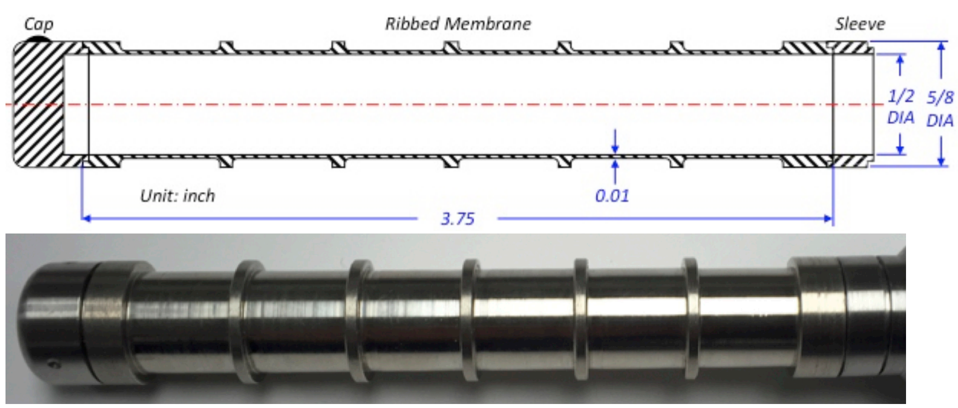


Figure 5. Design and photo of ribbed nickel membrane probe.

6.2 Creep-collapse Test Apparatus

Argonne has designed a creep-collapse test apparatus that consists of a high-pressure test chamber, a nickel membrane probe, a tube furnace, a pressure manifold, a vacuum manifold, a compact DAQ module, and a data acquisition computer. Figure 6 illustrates the experimental setup of the creep-collapse test apparatus. The apparatus has a maximum operating pressure up to 20.7 MPa (3,000 psi) and temperature up to 600°C. The pressure manifold consists of an argon gas bottle, a pressure regulator, pressure relief valve, pressure gauge, and control valves. The test chamber is approved for testing up to 2,000 psi. The chamber is placed in a tube furnace and heated to 560°C during creep-collapse tests. Membrane probes are tested between 200 psig to 1,000 psig until they fail for the estimation of the life expectancy of the membranes. The vacuum manifold equipped with a roughing pump to provide low vacuum, a pressure gauge to monitor pressure changes, and shut-off valve to isolate the pump. The compact DAQ module (NI-cDAQ9174) converts and transfers the analog measurements of the temperature and pressure of the nickel membrane probe and the pressure of the test chamber to the computer. Figure 7 shows the experimental apparatus of the creep-collapse test.

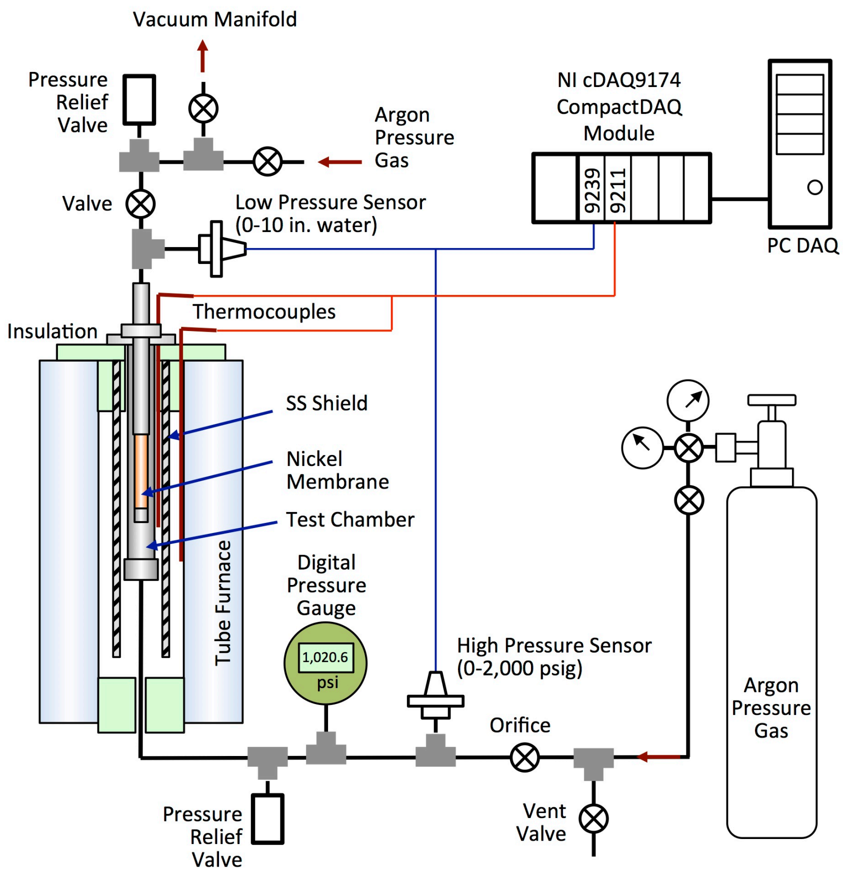


Figure 6. Diagram of the experiment setup of creep-collapse test.

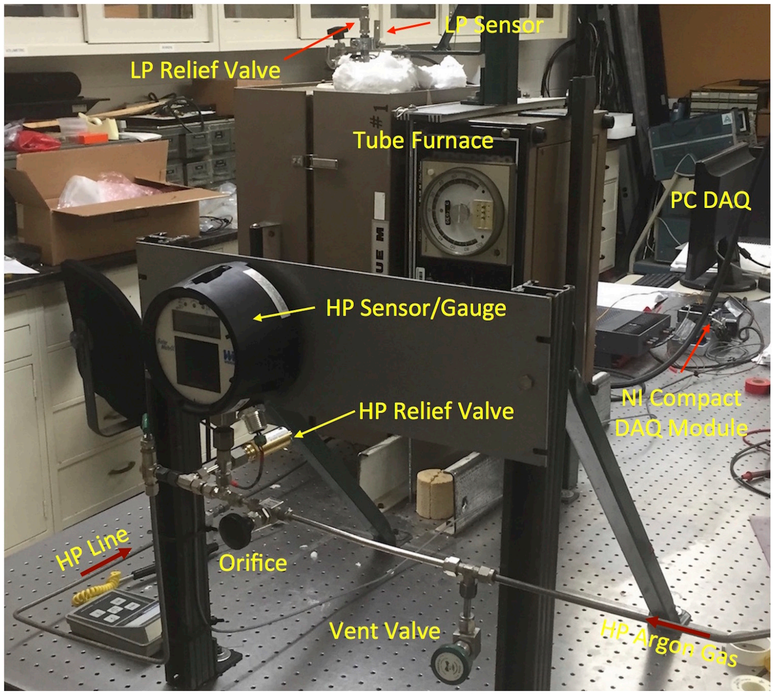


Figure 7. Experiment apparatus of creep-collapse test.

A test chamber, shown in Figure 8, was designed and fabrication. The chamber is 30.5 cm (12 in.) in length and 6.35 mm (1/4") in diameter. One end of the chamber connects to a high-pressure manifold and the other end is welded to a SS union, where a test probe will be mounted. The chamber has a maximum operating pressure up to 20.7 MPa (3,000 psig) and temperature up to 600°C. A graphic user interface (GUI) software on LabView® platform was also developed for data acquisition and real-time display of creep-collapse test.

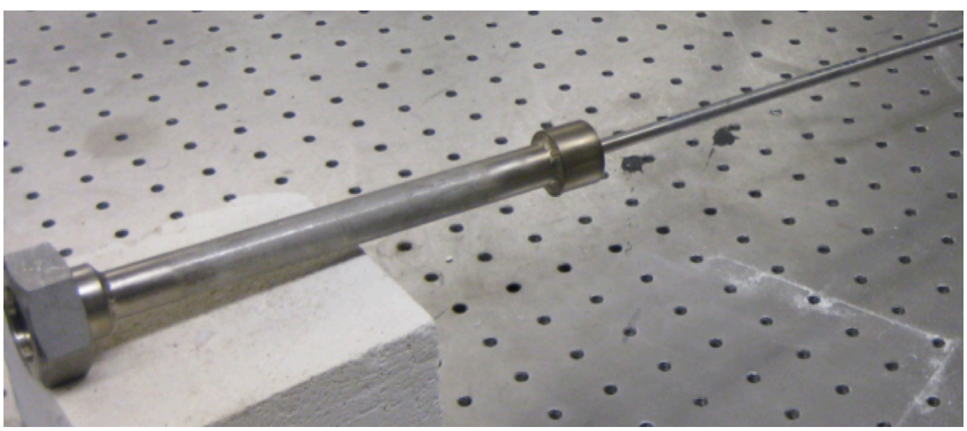


Figure 8. Test chamber for creep-collapse test.

6.3 Creep-collapse Test of Nickel Membranes

This section reports the creep-collapse test results of straight membrane probes of CGHM and ribbed membrane probes of ISHM.

6.3.1 Creep-collapse Test of Straight Nickel Membranes

A total of ten nickel membrane probes were fabricated. Six membrane probes are with membrane wall thickness of 10 mil and four are of 14 mil. Creep-collapse tests of these probes were all completed and the test results are reported in this section. Figure 9 shows a test chamber mounted inside the tube furnace for creep-collapse test. Figure 10 shows the experimental control panel and real-time displays of temperatures and internal pressures of nickel membrane and test chamber, respectively, during a creep-collapse test. To ensure test consistency, each test followed the same test procedure as the following:

1. Mount a membrane probe onto the test apparatus under ambient condition;
2. Conduct hydrostatic pressure test (or leak test) of the nickel membrane probe;
3. Gradually heat the membrane probe up to 600°C to prevent thermal shock;
4. Wait until the probe temperature is stabilized at 600°C;
5. Pressurize the chamber with argon gas from ambient to the designed test pressure with 50 psi increment and ~5 minutes step-up duration;
6. Cool the chamber down to ambient conditions after the probe is collapsed;
7. Inspect and/or measure the probe.

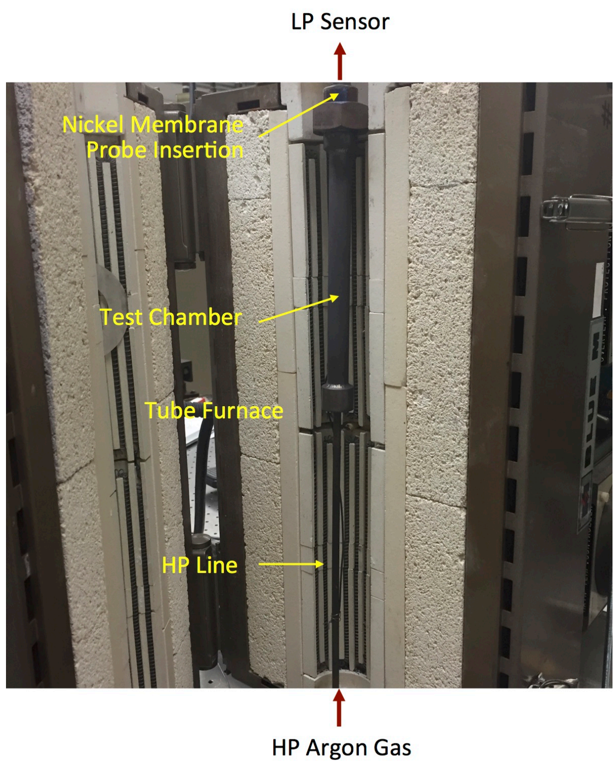


Figure 9. Test chamber mounted inside the tube furnace for creep-collapse test.

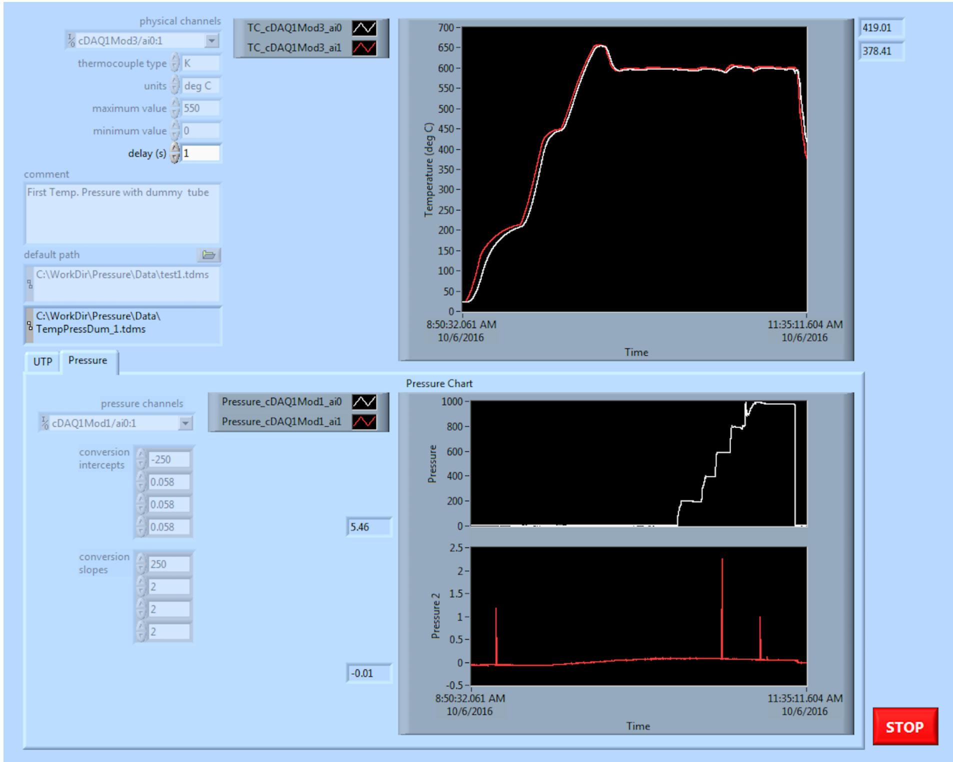


Figure 10. Creep-collapse test GUI control panel and timeline displays of (top) membrane temperature and (bottom) chamber and probe internal pressures.

The first eight membrane probes were fabricated with the original designs of flat cap and collar shown in Figure 2. All these probes were welded using the electron beam (EB) welding technique under vacuum condition to prevent dissipation of the electron beam. Seven were tested and all of them were collapsed at different pressures, except #10-1. After evaluation of the collapsed test probes and a discussion with welding experts at Argonne Central Shop, a different shape of cap and collar that might be able to reduce stress concentration or strength weakening of the welded ends of a membrane and to delay the membrane collapse. Cap and collar were redesigned to be bullet shape, rather than the original flat cylindrical shape. Figure 11 shows the redesigned bullet cap, collar, and redesigned membrane probe. Two additional membrane probes (probe #10-5 and #10-6), shown in Figure 10, were fabricated with bullet cap and collar design. In addition, two different welding techniques were used. The probe #10-5 was hand welded and #10-6 was EB welded.

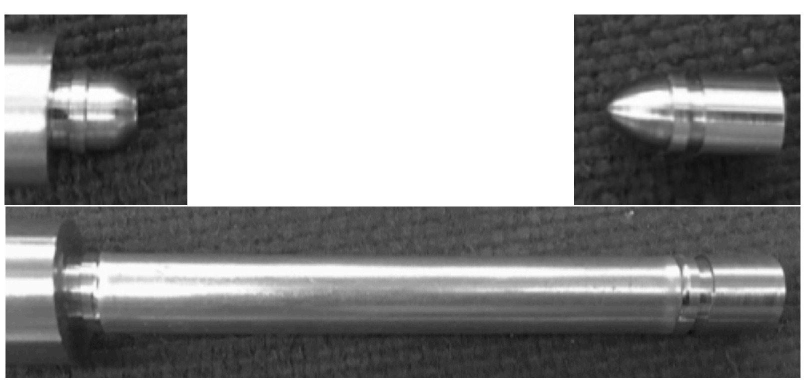


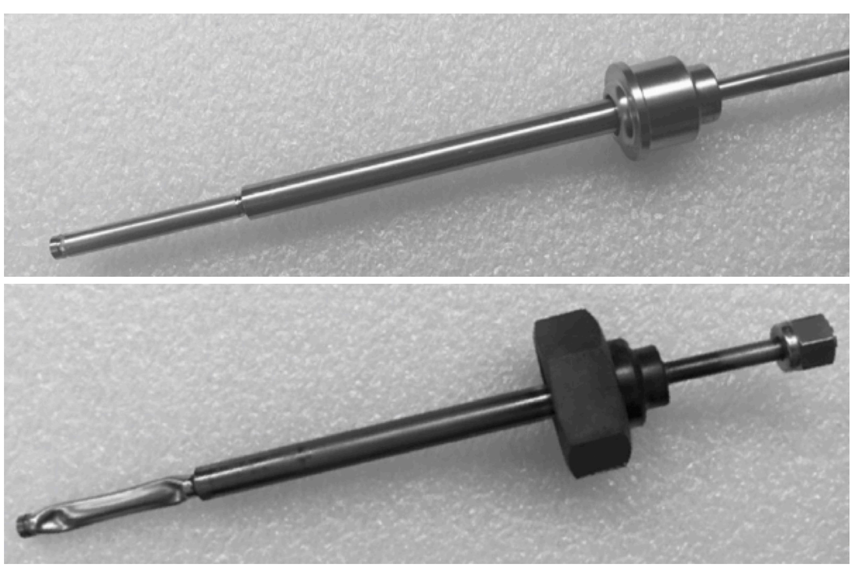
Figure 11. Designs of the bullet collar (left) and cap (right) of the membrane probe.

Two parameters, internal pressure of the membrane probe and deformation of the membrane (if not collapsed), were measured to determine membrane's integrity and to predict its life. All of the probes were tested under different designated pressures at temperature of 600°C. Table 3 summarizes the test conditions and test results of the ten membrane probes.

Table 4: Summary of the test conditions and test results of membrane probes

Probe No.	Wall Thickness (mil)	Cap/Collar Design	Pressure (psig)	Welding Method	Result	Survived Time	Test No.
#10-1	10	Flat	1,000	EB	Not Collapsed	1 hr 50 min	1
#10-2	10	Flat	1,000	EB	Collapsed	8 hr 2 min	3
#10-3	10	Flat	800	EB	Collapsed	28 min	5
#10-4	10	Flat	400	EB	Collapsed	4 hr 24 min	6
#14-1	14	Flat	1,000	EB	Collapsed	4 hr 13 min	2
#14-2	14	Flat	800	EB	Collapsed	2 hr 14 min	4
#14-3	14	Flat	300	EB	Collapsed	154 hr 15 min	7
#14-4	14	Flat	100-300	EB	Collapsed	2,805 hr 55 min	10
#10-5	10	Bullet	300	Hand	Collapsed	58 min	8
#10-6	10	Bullet	100-300	EB	Collapsed	31,681 hr	9

The first probe with wall thickness of 10 mil was tested at 1,000 psig for eight hours. Surprisingly, the probe survived and did not show any significant diameter changes at either the two ends or the middle of the nickel membrane. The following seven probes with wall thickness of 10 or 14 mil all collapsed, some even at 300 psig. Theoretically, the middle of the tubular membrane has the weakest strength and should collapse first. Conversely, test 2 indicates that the collapse started from the two welded ends, shown in Figure 12, of the membrane.



(a)
(b)

Figure 12. Nickel membrane probe #14-1 (a) before and (b) after creep-collapse test.

All the nickel membranes were inspected after receipt. Several nickel membrane probes have score marks along the length-direction, shown in Figure 13, caused by the extrusion process. It was a concern that the scoring could cause the collapse prematurely during testing. However, the test results show that no collapse happened at a location having a score-mark.

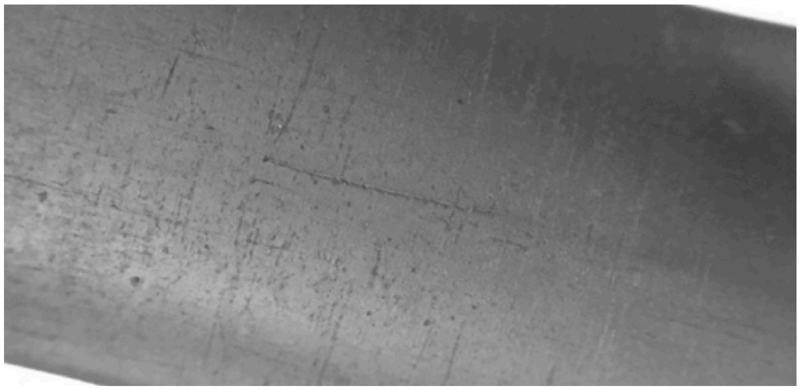


Figure 13. Mark caused by extrusion die on the nickel membrane probe #10-2.

Figure 14 shows the survival time of the ten membrane probes tested under different pressures from 300 to 1,000 psig at 600°C. Based on the test results, the life expectancy of the nickel membranes cannot be predicted at this moment. It is also inconclusive if the membrane's strength weakening is caused by either welding process, imperfection of the membrane, grain size/boundary at high temperature, stress concentration due to collar/end-cap shape, or other reasons. Surface analysis of the membranes before and after the creep-collapse test is needed to study creep-collapse phenomena, grain size and the boundary at high temperature, welding process, and quality of nickel membranes.

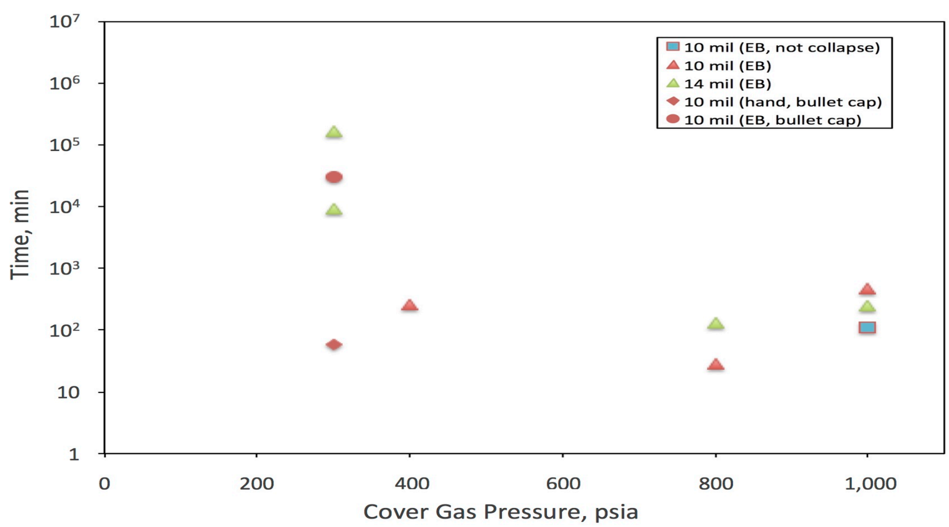


Figure 14. Survive time of ten membrane probes under different pressures at 600°C.

6.3.2 Creep-collapse Test of Ribbed Nickel Membranes

Two ribbed nickel membrane assemblies were fabricated for creep-collapse test. The thickness of the membranes is both 10 mil. Table 4 summarizes the test conditions and test results of the ten membrane probes. Two additional ribbed nickel membrane assemblies were fabricated and will be tested after the diffusion test of nickel coil tubing for in-situ calibration of CGHM.

Table 5: Summary of the test conditions and test results of ribbed membrane probes

Probe No.	Wall Thickness (mil)	Pressure (psig)	Temperature (°C)	Welding Method	Result	Survived Time	Test No.
#10-R1	10	300	600	EB	Collapsed	23 hours	1
#10-R2	10	109-300	540	EB	Collapsed	108 days	2

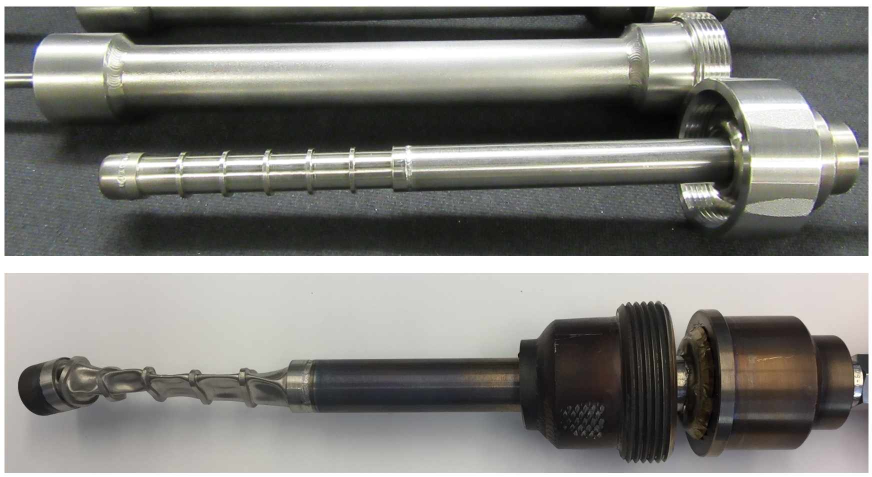


Figure 15. Nickel membrane probe #10-R2 (a) before and (b) after creep-collapse test.

The ten tubular nickel membrane probes were tested under different pressures from 300 psig to 1,000 psig at 600°C. Based on the creep-test results of the ten membrane probes for CGHM, the life expectancy of the nickel membranes cannot be predicted at this moment. It is also inconclusive that if the membrane's strength weakening is caused by the welding process, imperfection of the membrane, grain size/boundary at high temperature, stress concentration due to collar/end-cap shape, or other reasons. Surface analysis of the membranes before and after the creep-collapse test is needed to study creep-collapse phenomena, grain size and boundary at high temperature, welding process, and quality of nickel membranes. The straight membranes were extruded into the designed shape and dimensions (thickness and diameter) from nickel tubes. The ribbed tubular nickel membranes were milled down to the designated membrane thickness (10 mil) from an extruded nickel tube with 1/16" in thickness. It is recommended that the membranes be heat-treated at 1,300-1,500°F in an inert gas environment to remove stresses introduced into the material during the extruding, milling, and welding processes.

6.4 Strength Test of Ribbed Nickel Membranes

While in service, molten sodium flows around the nickel membrane of ISHM might induce vibrations on the membrane. Two test apparatuses were constructed to study flow-induced vibration of ribbed nickel membranes in water with different flowrates and strain/displacement of ribbed nickel membranes perturbed by a shaker with different vibration intensities. The test results are documented and discussed in this section.

6.4.1 Flow-induced Vibration of Ribbed Nickel Membranes

While in service, molten sodium flows around the nickel membrane at a rate of approximately 0.3 gpm, and might induce vibrations on the membrane and cause fatigue. To simulate the flow-induced vibration under different flowrates and determine the vibrational displacements of the membrane, a water flow-induced test apparatus was constructed. The ribbed nickel membrane was attached via welding at one end, similar to a cantilever beam. A laser vibrometer system (Polytek OFV 3000) was used to measure the displacement of the capped end of the membrane. Figure 16 shows the water flow-induced vibration test apparatus and Figure 17 shows a close look and side view of the test apparatus setup. Table 5 summarizes the test conditions of different tests.

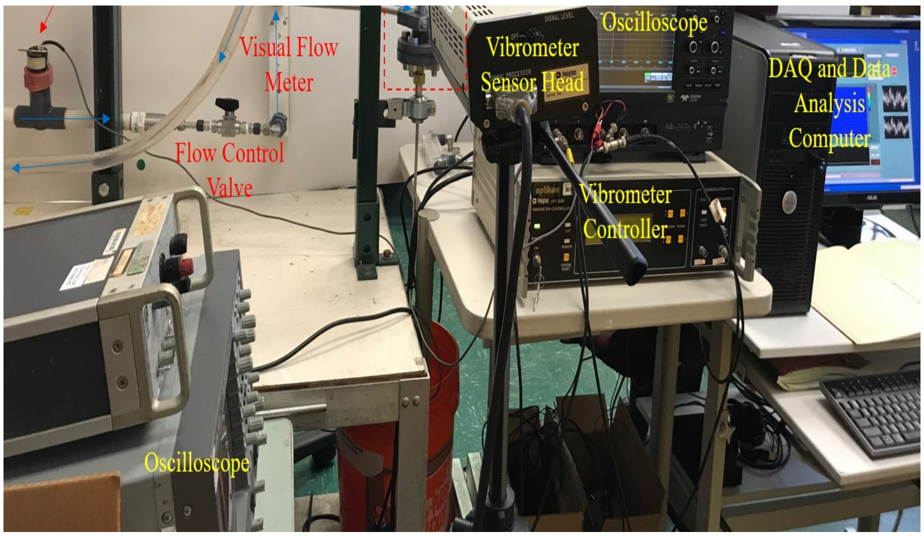


Figure 16. Water flow-induced vibration test apparatus.

Figure 17. Close up of membrane, cap, and clear PVC housing and (right) side view of water flow-induced vibration test apparatus.

It was verified that the vibrometer could consistently measure the vibration of the membrane at static mode, i.e. at zero flowrate. Although displacement generally increased with flow rate, at dynamic mode, the vibration measurements were inconsistent. It is suspected that the measurements were combined with the vibrations of the PVC housing and the membrane. Since we had trouble to decouple the vibrations of the PVC pipe and membrane from the measurements, the results of these tests are inconclusive. However, it is worth noting that the vibrational displacement of the entire assembly and housing seem to have increased due to the disturbance of flow caused by the flow control valve. While the displacements increased somewhat linearly for flow rates of 1-3 gpm, the displacements increased greatly at 4 gpm, then dropped when the flow was 5 gpm.

6.4.2 Strain/Displacement Measurements of Ribbed Nickel Membranes

A test apparatus has been also constructed to investigate the strain/displacement measurements of ribbed nickel membranes caused by flow-induced vibration. The test apparatus consists of a ribbed nickel membrane assembly, two strain gauges, a mechanical shaker, an accelerometer, and an optic vibrometer system. The ribbed nickel membrane assembly is mounted horizontally and perturbed by a shaker with different vibration intensities at the holding rod. Two strain gauges were mounted at the base of the membrane before the holding rod. One stain gauge is oriented along the axial direction of the membrane and the other along the circumferential direction. The vibrometer is set perpendicular with the membrane and measures the displacement of the cap of the membrane assembly. An accelerometer is mounted on the top of the membrane's cap to measure also the displacement of the cap of the assembly. Figure 18 shows a picture of the test apparatus of strain/displacement measurement. The tests are in progress and the results will be reported in the future.

Table 6: Summary of the water flow-induced vibration tests

Test #	Flow Rate (gpm)	Duration (min)	Vibrometer Position
1-9	1, 2, 1.5	30	50.8 cm West of membrane center; vibrometer aimed at cap, ~225 degrees clockwise from water inlet
10	2	30	101.6 cm West of membrane center; vibrometer aimed at cap, ~225 degrees clockwise from water inlet
11-19	1, 2, 1.5	30	50.8 cm South of membrane center; vibrometer aimed at cap, ~135 degrees clockwise from water inlet
20	0	30	50.8 cm South of membrane center; vibrometer aimed at cap, ~135 degrees clockwise from water inlet
21	0	30	50.8 cm West of membrane center; vibrometer aimed at cap, ~225 degrees clockwise from water inlet
22-25	1, 2, 1.5, 0	30	50.8 cm West of upper flange; vibrometer aimed at upper flange, ~225 degrees clockwise from water inlet
26-43	0, 1, 2, 3, 4, 5	10	50.8 cm West of membrane center; vibrometer aimed at cap, ~225 degrees clockwise from inlet
44-61	0, 1, 2, 3, 4, 5	10	50.8 cm South of membrane center; vibrometer aimed at cap, ~135 degrees clockwise from inlet
62	3	10	49.53 cm West of membrane center; vibrometer aimed at cap for benchmark, ~225 degrees clockwise from water inlet
63	3	10	49.53 cm West of membrane center; vibrometer aimed at PVC just above cap so it passed through to door 10-15 ft behind it which was tapped on 10 times every 2 minutes, ~225 degrees clockwise from water inlet
64	3	10	49.53 cm West of membrane center; vibrometer aimed at PVC just above cap so it passed through to door 10-15 ft behind it, ~225 degrees clockwise from water inlet
65	3	10	49.53 cm West of membrane center; vibrometer aimed at PVC just above cap so it passed through to poster ~15 inches behind it which was tapped on 10 times every 2 minutes, ~225 degrees clockwise from water inlet
66	3	10	49.53 cm West of membrane center; vibrometer aimed at cap for benchmark, ~225 degrees clockwise from water inlet
67	3	5	50.8 cm West of membrane center; vibrometer aimed at cap for benchmark, ~225 degrees clockwise from water inlet
68	3	5	50.8 cm West of membrane center; vibrometer aimed at PVC just above cap so it passed through to door 10-15 ft behind it, ~225 degrees clockwise from water inlet
69	3	5	50.8 cm West of membrane center; vibrometer aimed at upper flange, ~225 degrees clockwise from water inlet
70	3	5	50.8 cm West of membrane center; vibrometer aimed at cap for benchmark, ~225 degrees clockwise from water inlet
71	3	5	50.8 cm West of membrane center; vibrometer aimed at PVC just above cap so it passed through to door 10-15 ft behind it, ~225 degrees clockwise from water inlet

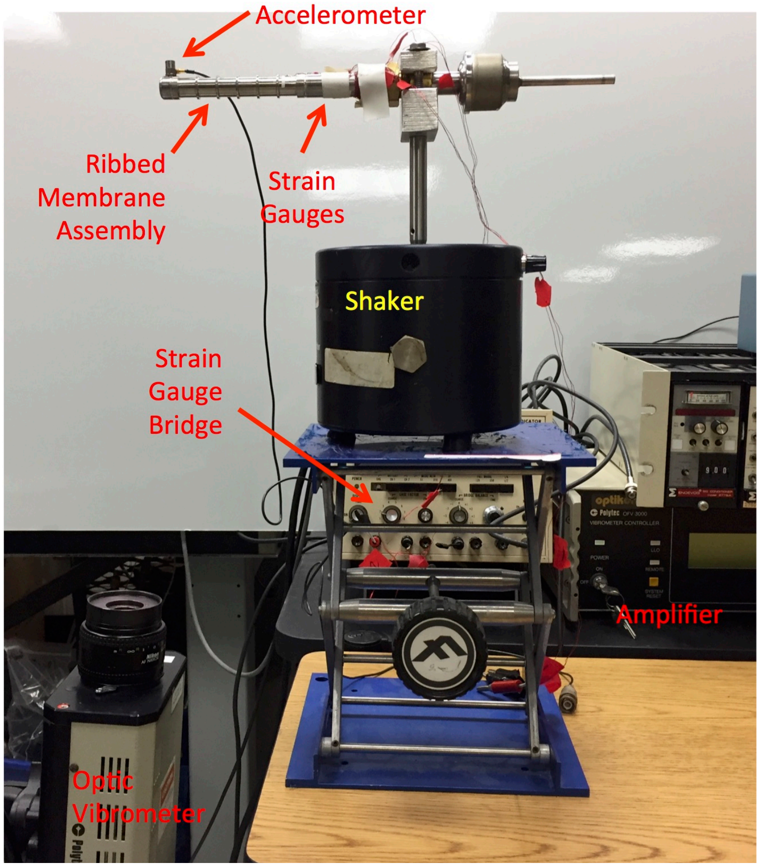


Figure 18. Test apparatus of strain/displacement measurement.

7 DIFFUSION-TYPE COVER-GAS HYDROGEN METER

Argonne has designed a CGHM for real-time, in-situ monitoring of hydrogen concentration in the cover gas of an expansion tank. A CGHM consists of four major modules, a nickel membrane probe, a vacuum manifold and hydrogen measuring system, a hydrogen injection system, and a standpipe unit. Figure 19 shows the basic design and physical arrangement of the proposed nickel membrane probe assembly to be installed in sodium expansion tank. To deploy for use, the standpipe will be welded to the expansion tank. The probe assembly is inserted in the standpipe and sealed onto the standpipe using a standard ring-joint pipe flange. The vacuum line leads through an ionization gauge and an isolation valve to an ion pump. The pipe flange also provides feed through for a thermocouple, heater, and hydrogen injection coil.

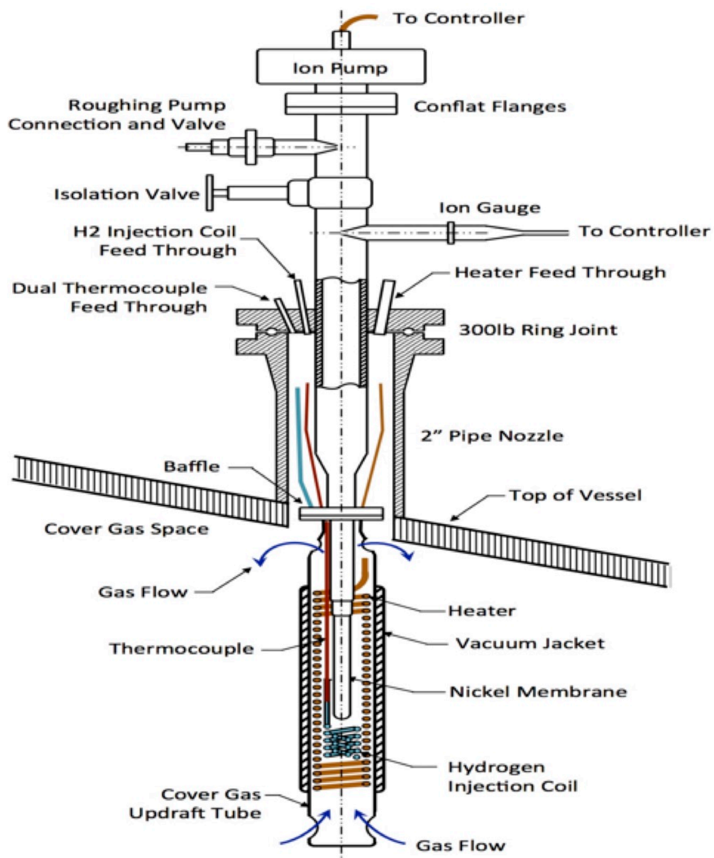


Figure 19. Basic design and physical arrangement of CGHM.

7.1 CGHM Membrane Assembly

This section describes the design revisions of the major components of the nickel membrane probe. A nickel membrane assembly consists of a nickel membrane, a heater, a hydrogen injection coil, a heater support, a baffle, a flange unit, and a vacuum manifold. Figure 20 shows a revised membrane assembly that consists of a redesigned membrane probe and baffle and an additional membrane holder specifically for laboratory performance evaluation. For reactor deployment, to avoid potential cover gas leaking if the nickel membrane failed, the original design has the membrane probe welded on to the baffle, which is then welded with the flange unit and then to the vacuum manifold. For laboratory testing, there is no such concern. In case service is needed during a test, it would be convenient if the membrane probe could be easily removed from the assembly. A design revision was made such that the membrane probe is welded to a long membrane holder, rather than to the baffle. The holder has a union welded on the other end and connected to the manifold. Two prototypes were fabricated for performance evaluation. Figure 21 shows a photo of the CGHM membrane assembly prototype #1.

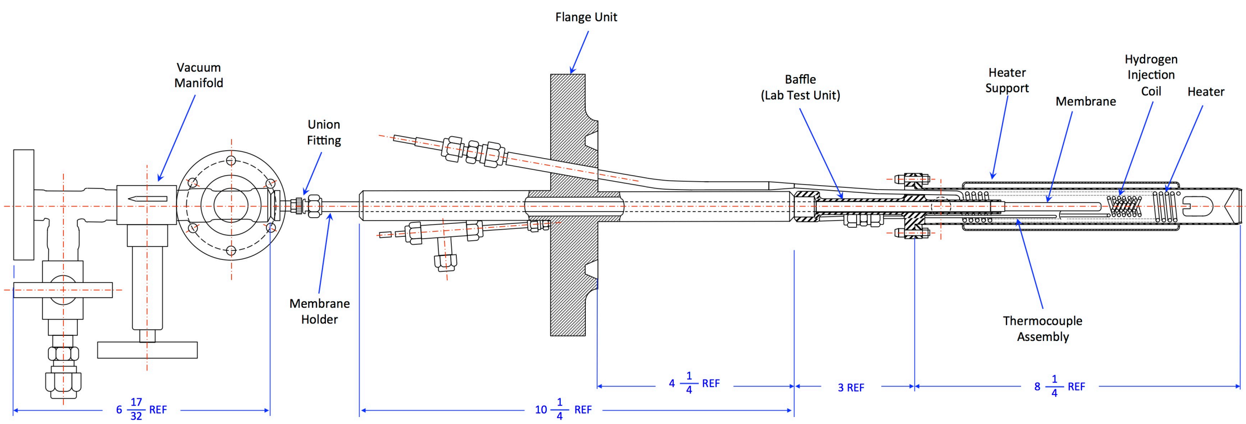


Figure 20. Revision of CGHM membrane assembly for laboratory test.

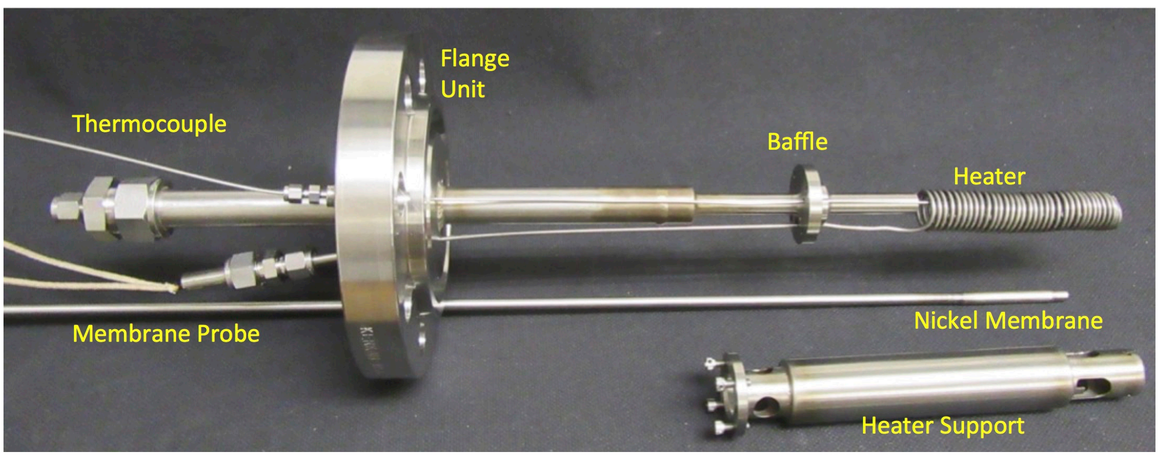


Figure 21. Photo of CGHM Membrane Assembly Prototype #1.

Nickel Membrane Probe

The probe consists of a nickel membrane of 6.359 mm in ID, 0.254 mm (10 mil) in wall thickness, and 50.8 mm (2 in.) in length. It provides a total active surface of 10.14 cm^2 for hydrogen diffusion and a volume of 1.6 cm^3. A welding expert at Argonne recommended that the welding legs of both nickel collar and cap should be increased to provide a stronger support and to avoid any stress concentrations. Figure 2 shows the revised design of nickel membrane.

Hydrogen Injection Coil

Hydrogen injection coil is mainly for in-situ CGHM calibration. The injection coil is a 1/16" thin-wall nickel-201 tube placed directly below the membrane. The coil will be connected to a hydrogen injection system to provide predetermined hydrogen concentrations at the membrane for meter calibration. The injection system consists of primarily a hydrogen source (or hydrogen/argon mixture), a pressure regulator, pressure gauges, control valves, and a mass flow controller. During calibration, the nickel coil is pressurized with hydrogen gas or hydrogen-argon mixture and heated up to 640°C by the membrane heater (described in the previous section). Depending on the hydrogen concentration in the nickel coil, a known hydrogen amount then will be diffused into the test vessel.

Membrane Heater

A resistance heater, 115 VAC and 250 Watts, surrounds and heats the capped nickel membrane up to 560°C under normal operation, or from 370°C to 560°C during performance evaluation. The heating wire is 120 in. long and ~90 mil in diameter. A bending arbor of 5/8 in. in diameter will be used to coil the heating wire in shape. It is then stretched to ~5.5 in. to cover both membrane and hydrogen injection coil. Two thermocouples (type K) are located close to the membrane. One is connected to a temperature indicator and a NI compact DAQ module, and the other to a heating controller.

Heater Support

A heater support is used to support both of the membrane heater and the hydrogen injection coil. The heater support has three inlets and outlets at the lower and upper wall for cover gas/hydrogen to flow through the meter. The support also consists of a vacuum chamber (or jacket) surrounding the membrane heater to keep the membrane at the designed temperature and to establish a thermal updraft of cover gas around the membrane, therefore speeding up hydrogen entering the meter. A cone disc is placed at the bottom of the support to collect sodium condensation, which is then drained out through the three drainage holes at the bottom of the support's wall.

Baffle

A baffle is designed to restrain the hydrogen diffusing into the nickel membrane probe and to an ion pump. The baffle is redesigned for laboratory test. One end of the baffle is welded onto the SS tube of the flange unit, which connects to the vacuum system. Rather than directly welded a nickel membrane at the other end, the inner diameter of the baffle is increased to allow a membrane probe to feed through the baffle. It still consists of the same flange that is used to mount the membrane-baffle assembly onto a heater support.

Membrane Holder

For laboratory test, in case service is needed, it would be convenient if the membrane probe could be easily removed from the assembly. A long membrane holder was designed. One end of the holder is welded to the membrane probe and the other end is welded to a union fitting, which connects to the vacuum manifold.

Flange Unit

A flange unit consisting of a ring joint blind flange (2 in, 300 lb) and a tube (¾ in. in diameter, 10.25 in. in length) feeding through the center of the flange. One end of the tube is welded with a baffle and other end is welded to a vacuum manifold. After inserting the nickel membrane probe into a test vessel for performance evaluation or the standpipe for deployment, the flange then provides a vacuum-tight seal. The flange also provides sealed feedthroughs for hydrogen, the thermocouple, and heater power.

Vacuum Manifold

A vacuum manifold consists of two valves and fittings that connect to a nickel membrane probe at one end and to a vacuum and hydrogen measuring system at other end. The vacuum end of the probe leads through an ionization gauge and an isolation valve and then to an ion pump. The isolation valve is used to isolate the probe and ionization gauge from the ion pump when the equilibrium mode of operation is desired. Both valves are all-metal bakeable and are capable of high-vacuum operation. Connections are either welded (preferred) or incorporate ConFlat flanges with nickel gaskets. A roughing valve connected to a roughing pump is used at startup or in case of loss of vacuum of a probe. Usually, after the probe and measuring system are baked out, vacuumed, the roughing valve is then closed and the end of the vacuum tubing to roughing pump is sealed. The CGHM probe is then ready to be removed from the pump for deployment or testing.

7.2 Pilot Test Apparatus of CGHM Prototypes

A laboratory pilot test apparatus was constructed for the performance evaluation of the CGHM prototypes. The apparatus consists of a CGHM probe assembly, a test vessel, a vacuum and hydrogen measuring system, hydrogen injection system, and instrumentation and control (I&C) system. Figure 22 shows the experimental setup of the pilot test apparatus and Figure 23 shows a photo of the fully assembled pilot test apparatus.

Based on the findings of the creep-collapse test, two CGHM prototypes were fabricated for performance evaluation to determine sensitivity, response time, and reproducibility of the CGHM prototypes. A CGHM probe assembly will be integrated with the vacuum and hydrogen measuring system. The integrated assembly then will be baked out before each test. For performance evaluation, gas mixtures with different hydrogen concentrations will be fed into the test vessel, which will be vacuumed after each test. The evaluation of in-situ calibration of the meter also will be conducted. During calibration, the nickel coil is heated by the membrane heater and pressurized with hydrogen gas or hydrogen-argon mixture. The tests will also evaluate and validate the calibration requirements and procedures proposed in this report. The optimal meter operating conditions will then be determined.

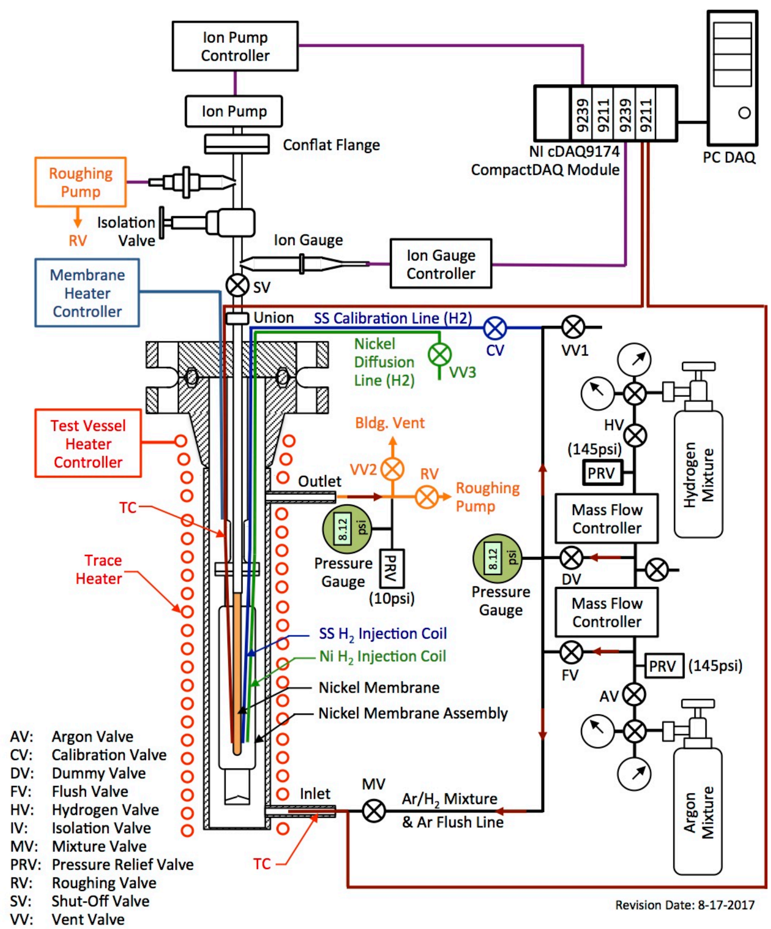


Figure 22. Pilot testing apparatus for performance evaluation of CGHM prototypes.

Figure 23. Photo of the fully assembled pilot test apparatus.

7.3.1 Design of Pilot Test Vessel

For laboratory performance evaluation of CGHM prototypes, a pilot test vessel, similar to that of a standpipe unit, was designed and fabricated for maximum operation temperature of 800C and maximum vessel pressure of 1,200 psig. Figure 24 shows a photo of the vessel taken before hydrostatic pressure and leak tests. It consists of a ring-joint flange, a SS pipe, and two gas ports. The chamber is 5.4 cm (2.125 in.) in diameter and 41 cm (16.125 in.) in length. The bottom of the pipe is capped with a SS plate and the top is welded onto the flange. It is heated up to the temperature (~332°C) of an expansion tank by band heaters. A K-type thermocouple is inserted through the inlet gas port (bottom) to monitor the temperature of the argon cover gas in the vessel. The gas line connected to the inlet port will be also heated to the designed temperature of the cover gas to simulate the actual reactor operation condition and to minimize thermal impact to the meter. Different hydrogen/argon gas mixtures are then injected through the gas inlet port into the vessel for the performance evaluation of CGHM prototypes.

Figure 24. Photo of the test vessel for laboratory pilot test.

7.3.2 Vacuum Manifold and Hydrogen Measuring System

A vacuum and hydrogen measuring system is required to prepare and test a CGHM. The system is an all-metal bankable system, capable of high vacuum operation. It consists of the following major components:

- Cryogenic roughing pump (1-10^{-3} Torr) (oil-free pump)
- Ion pump (10^{-7} to 10^{-8} Torr)
- Ti-sublimation pump (10^{-8} to 10^{-9} Torr) (optional)
- Gate valve between Ti-pump and vacuum chamber
- Ion pump power supply
- Ionization gauge
- Ionization gauge controller
- Isolation valve between ion pump and ionization gauge
- Heaters and controllers
- Thermocouples and TC meters

The roughing pump is used for the startup to vacuum the manifold and the connected CGHM. A roughing valve connects the roughing pump to an isolation valve, which is used to isolate the probe and the ionization gauge from the ion pump when the equilibrium mode of operation is desired or remove the probe or ion pump for service. Heaters will be wrapped around the manifold for use during bakeout. Thermocouples will also be attached on ion pump and ionization gauge for temperature monitoring.

7.3.3 Hydrogen Injection System

The hydrogen injection system consists primarily of argon, hydrogen and hydrogen-argon mixture sources, a pressure regulator, pressure gauges, an MKS gas flow control unit, vacuum pump, and flow manifold. MKS gas flow control unit mixes argon and hydrogen-argon mixture to a designated ratio from 2.5% down to 1 ppm with different flow rates.

7.3.4 Instrumentation and Control (I&C) System

The I&C system will be developed to operate the pilot test facility. The system consists of three major modules: CGHM, leak analyzer, and control and display (C&D). The details of each module is described below:

CGHM Module

The CGHM module consists of a CGHM prototype, a vacuum manifold, and a test chamber as described in the previous sections. The module provides pressure/current of ionization gauge to the leak analyzer for leak and leak changing rate analysis. It also provides some operational data, such as temperatures of membrane and test chamber and pressure of ion pump, for the evaluation and determination of optimal operation condition. Different hydrogen/argon gas mixtures will be injected through the gas port into the argon cover gas for the performance evaluation of the prototype.

Leak Analyzer

The leak analyzer consists of a data acquisition (DAQ) system and a computer. The DAQ performs analog/digital (A/D) conversion of data, including temperatures, pressures, and currents, from the DTHMs module. The computer conducts the calculation and conversion of leak rate and leak changing rate. An initial calibration of each prototype will be conducted to provide the qualitative correlations between the pressure/current of ionization gauge to hydrogen concentration in the vacuum chamber. The change of leak rate can be determined from the slope of leak rate versus time.

<u>Control and Display</u>

The C&D module is used to operate the pilot test facility and to display leak rate and some critical operational information. Two sets of data are transferred from the computer to the module. One set includes water leak rate and leak changing rate. Table 7 summarizes the control variables and their settings for the CGHM pilot test.

Table 7: List of control variables and settings of CGHM

Device	Variable	Setting	Remark
Ionization Gauge TC	Temperature (T_{IG})	450°C	For bakeout
Membrane TC	Temperature (T_M)	370 - 560°C (typical 560°C)	Heat up the membrane gradually to the operating temperature
Cover Gas TC	Temperature (T_M)	450 - 510°C	Heat up the test vessel gradually to the operating temperature
Roughing Pump	Pressure (P_{RP})	< 10^{-4} mbar	Shut off when ionization pump kicks on ($P_{RP} < 10^{-4}$ mbar)
Ion Pump	Current (I_{IP})	(Undecided)	Ion Pump Controller converts P_{IP} to I_{IP} (device dependent)
	Pressure (P_{IP})	< 10^{-11} mbar	Kick on when $P_{RP} < 10^{-4}$ mbar
Ionization Gauge	Current (I_{IG})	(Calibration)	Ionization Gauge Controller converts P_{IG} to I_{IG} (device dependent)
	Pressure (P_{IG})	(Calibration)	

7.3 Performance Evaluation of CGHM Prototypes

Two CGHM prototypes were fabricated for performance evaluation. The pilot test of the prototype #1 was completed and the pilot test of the prototype #2 is still in progress. There are two hydrogen measurement modes, dynamic and equilibrium, to determine hydrogen concentration. In general, the ion pump current reflects the hydrogen flux diffusing through the nickel membrane and thus it gives a dynamic mode of hydrogen measurement. The ionization gauge also gives a measure of hydrogen pressure. If the ion pump is isolated, the ionization gauge gives an equilibrium mode measurement of hydrogen pressure, which represents the hydrogen partial pressure in cover gas or the hydrogen concentration in sodium. Detection sensitivity of a DTHM, either CGHM or ISHM, is therefore determined by the gauge sensitivity in detecting the pressure variation on the vacuum side of the meter. The pressure variation depends on the amount of hydrogen gas flowing in the vacuum system per unit time, the pumping speed, and the outgassing from the wall and gauges. In general, the wall outgassing can be neglected in most cases, especially during the dynamic run.

7.3.1 Effect of Temperature Controllers

At the beginning of the pilot tests of the prototype #1, a PID-based programmable temperature controller (HTS Amptek) was used to control the temperature of the membrane heater. Due to temperature fluctuation caused by PID-based programmable temperature controller, it was difficult to detect hydrogen concentration accurately and consistently, especially for hydrogen concentrations lower than 10 ppm. By switching to a variac transformer, the temperature fluctuation issue was resolved. Figures 25 and 26 show the CGHM prototype #1 responded to different hydrogen concentrations using HTS Amptek temperature controller and a variac transformer, respectively.

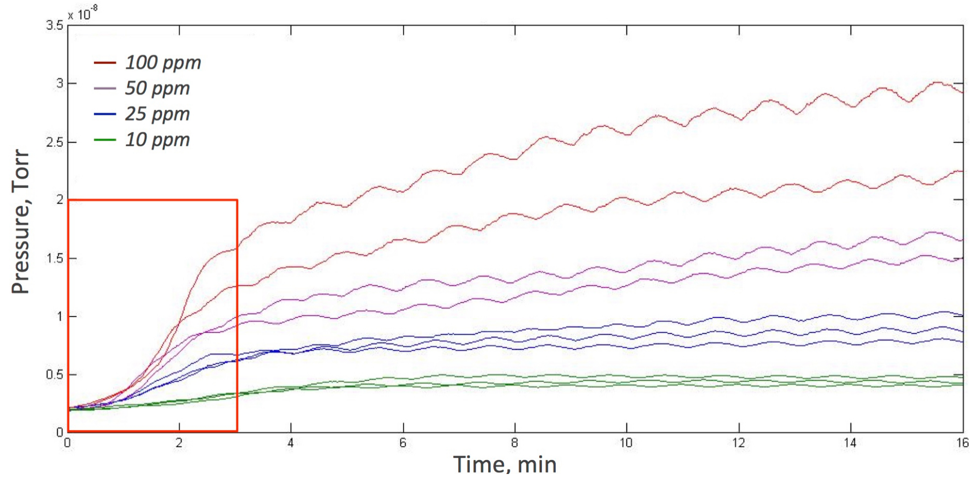


Figure 25. Responses to different H_2 concentrations using a PID temperature controller.

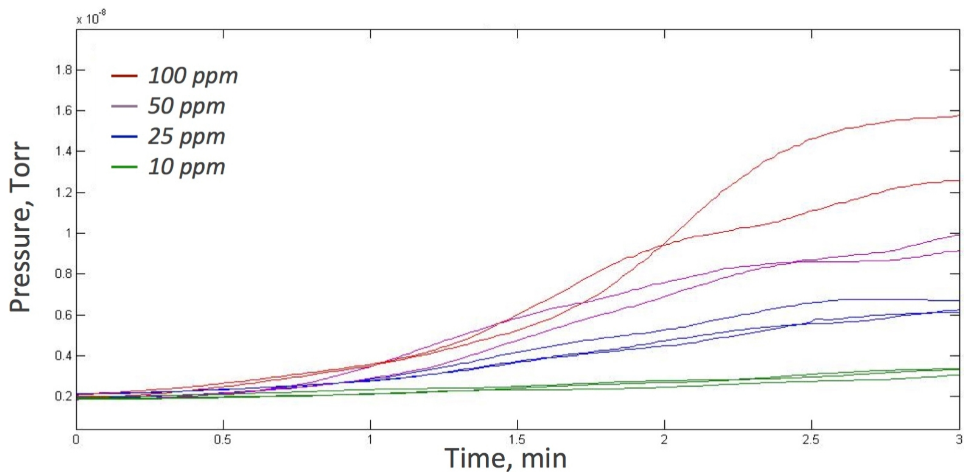


Figure 26. Responses to different H_2 concentrations using a variac transformer.

7.3.2 Dynamic Mode

Operation under the dynamic mode, the ion pump current reflects the hydrogen flux diffusing through the nickel membrane and the ionization gauge also a measure of hydrogen pressure. The temperature of the nickel membrane is at 650°C and the test vessel is at 450°C. Figure 27 and 28 show the response of prototype #1 to different concentrations of hydrogen flowing into the test vessel in vacuum at flow rate of 500 sccm and 1,000 sccm, respectively. The results indicate that the prototype is able to detect hydrogen as soon as a small hydrogen differential pressure between the internal and external of the nickel membrane is produced. The pressure change is used to determine the hydrogen concentration, i.e. how large is the steam/water leak of a SG; the rate of pressure change is an indication of steam/water leak changing rate. Figure 29 and 30 show response of prototype #1 to different concentrations of hydrogen flow into the test vessel covered with argon at flow rate of 500 sccm and 1,000 sccm, respectively.

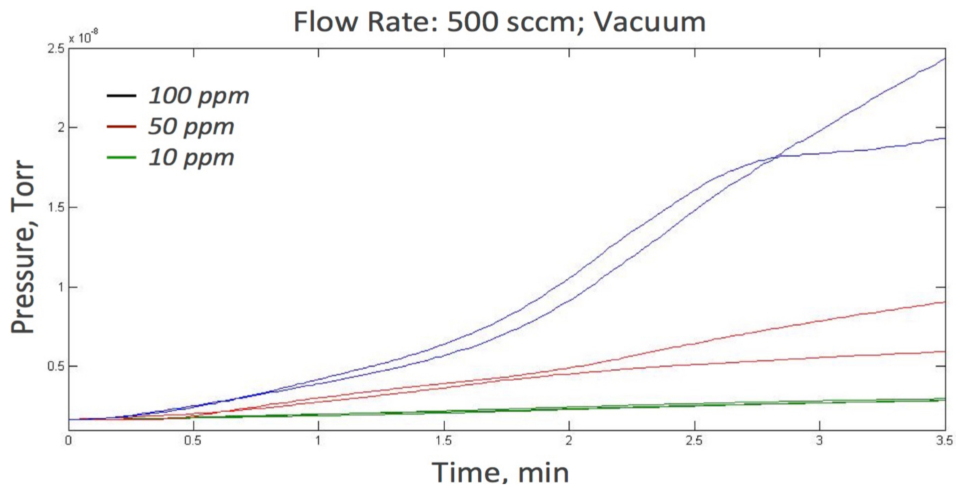


Figure 27. Response to different H_2 concentrations in vacuum at H_2/Ar flow rate of 500sccm.

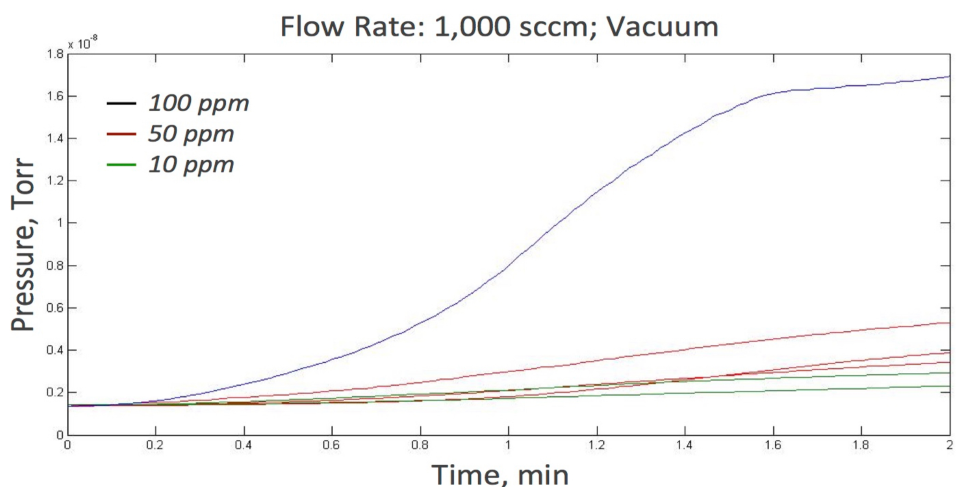


Figure 28. Response to different H_2 concentrations in vacuum at H_2/Ar flow rate of 1,000sccm.

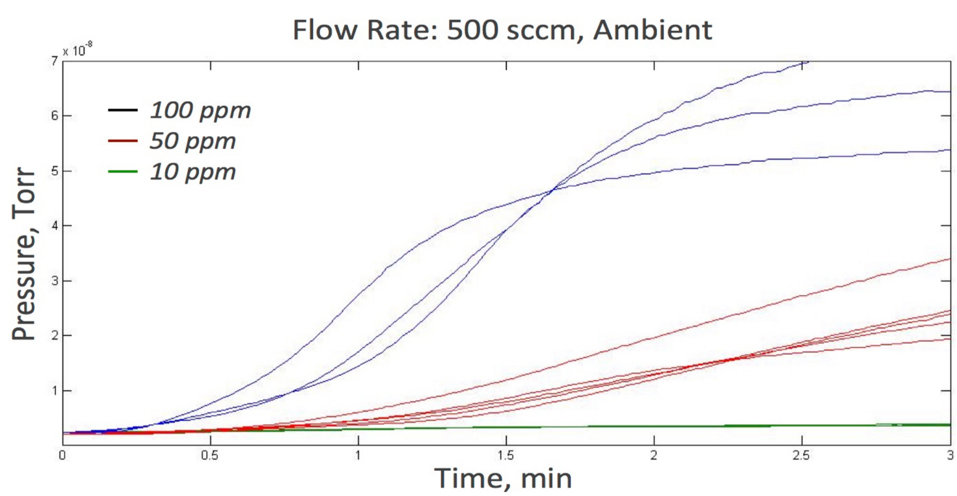


Figure 29. Response to different H_2 concentrations in argon at H_2/Ar flow rate of 500sccm.

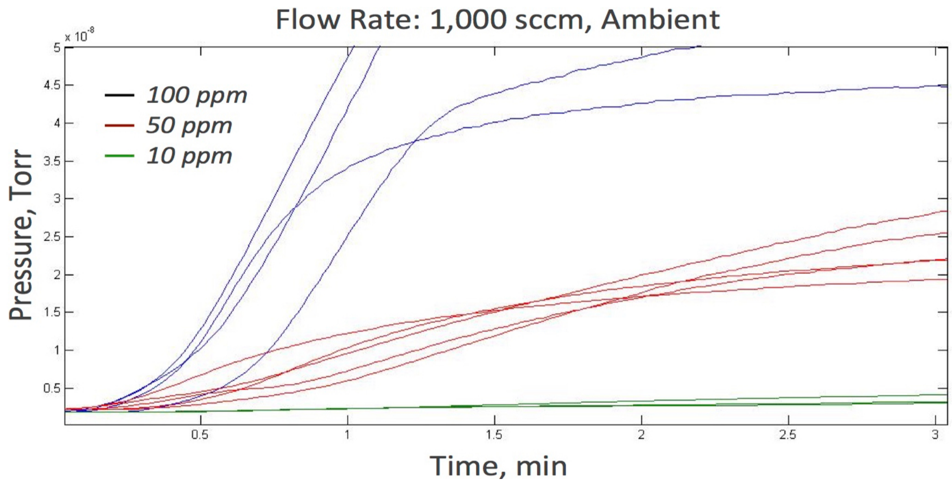


Figure 30. Response to different H_2 concentrations in argon at H_2/Ar flow rate of 1,000sccm.

Figure 31 shows the response time of prototype #1 to different H_2/Ar mixture flowing into the test vessel covered with vacuum and argon at different flow rates. The higher flowrate or hydrogen concentration show a higher pressure change as well as a higher pressure changing rate. The response time is faster for gas mixtures flowing into vacuum than into argon cover gas. A larger pressure change was observed for hydrogen mixtures flowing into an argon covered test vessel. The slope, i.e. pressure changing rate, is larger for higher flow rates, as well as for flowing into argon cover gas.

Based on the design of the test apparatus, the H_2/Ar mixture transporting time from the MKS mass flow controller outlet to the test vessel inlet for different flow rates are as following:

- Flow rate @ 1000 sccm: ~5 sec;
- Flow rate @ 500 sccm: ~10 sec.

The CGHM response time are estimated as the following:

- Vessel & transport line @ ambient: 1 sec to 10 sec (depending on flow rate , hydrogen concentration, and vessel dimension);
- Vessel & transport line @ vacuum: ~1 sec.

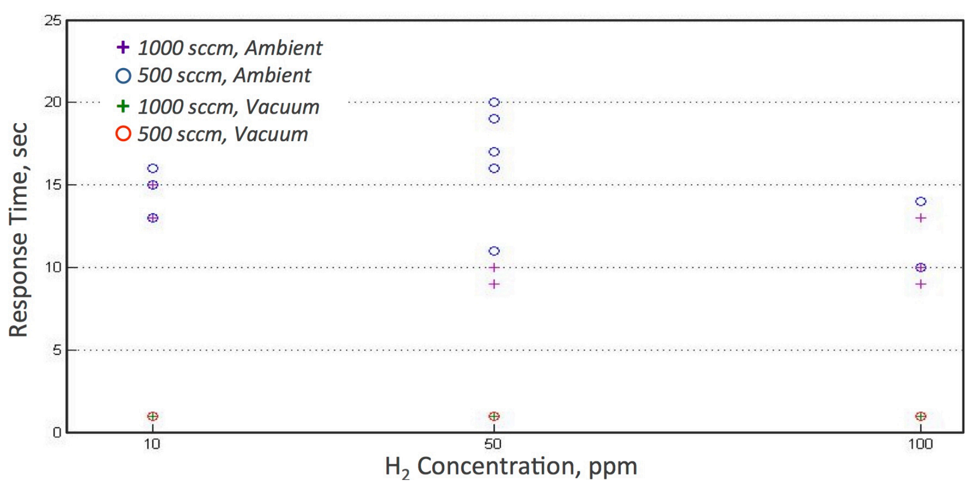


Figure 31. Response time to different H_2 concentrations at different flow rates.

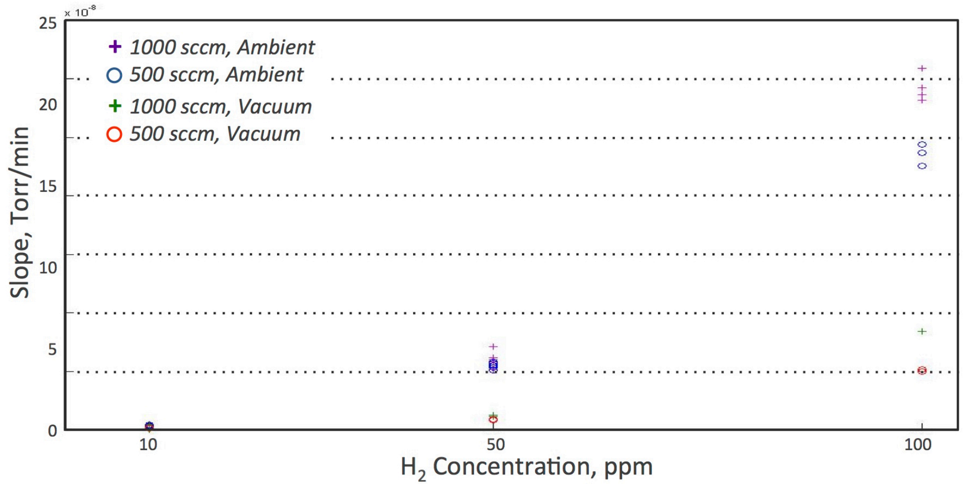
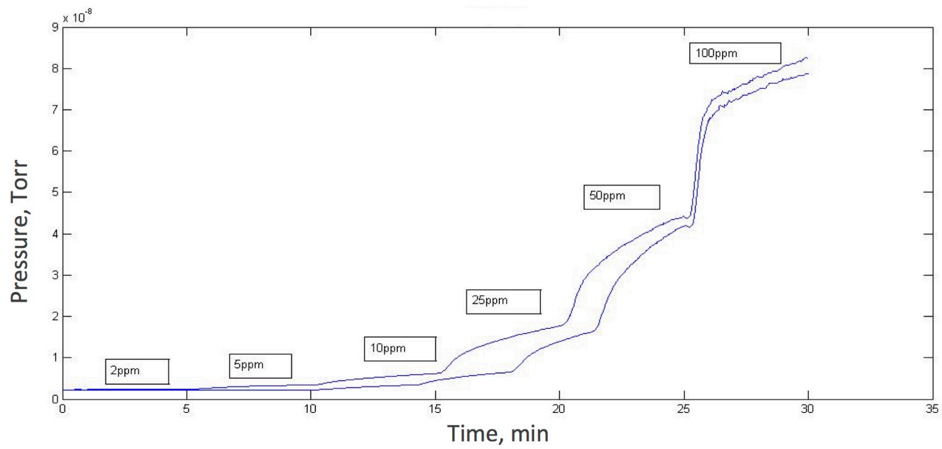
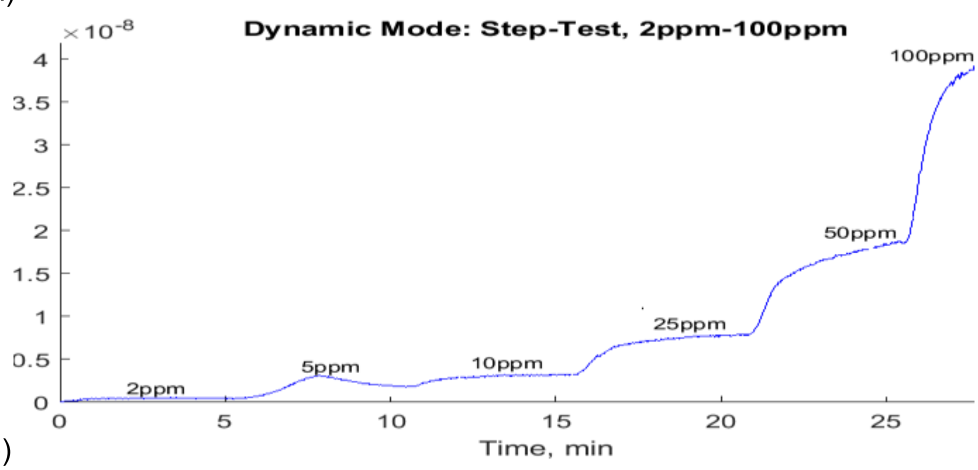


Figure 32. Pressure changing rate (slope) to different H_2 concentrations at different flow rates.

Hydrogen concentrates were systematically stepped up and down to investigate the pressure changes associated with different hydrogen concentrates. Figure 33 shows the results of tests of hydrogen concentrations stepping up from 2 ppm to 100 ppm for both prototype #1 and #2. Both figures show fast response time and larger slope for higher hydrogen concentration. Similar tests were conducted for hydrogen concentrations stepping down for prototype #1.



(a)



(b)

Figure 33. Response of prototype (a) #1 and (b) #2 to H_2 concentrations stepping up.

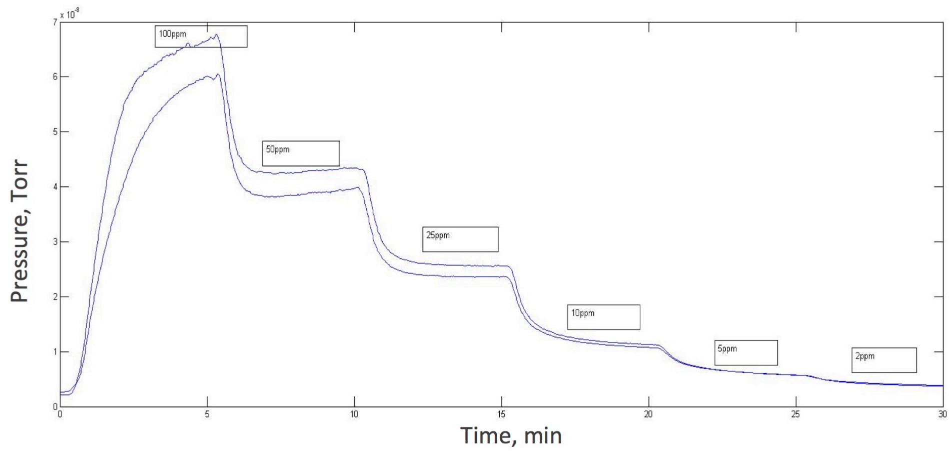


Figure 34. Response of prototype #1 to H_2 concentrations stepping down.

The diffusion rate of a nickel membrane depends on its thickness and temperature. The membrane of the CGHM is 10 mil. To study the effect of membrane temperature, the pressures of the ionization gauge were measured at different hydrogen concentrations with different membrane operating temperatures. Figure 35 shows the pressure of prototype #2 to hydrogen concentrations at different membrane temperatures. The membrane shows more consistent measurement and detection sensitivity when operated at the designed temperature (560°C).

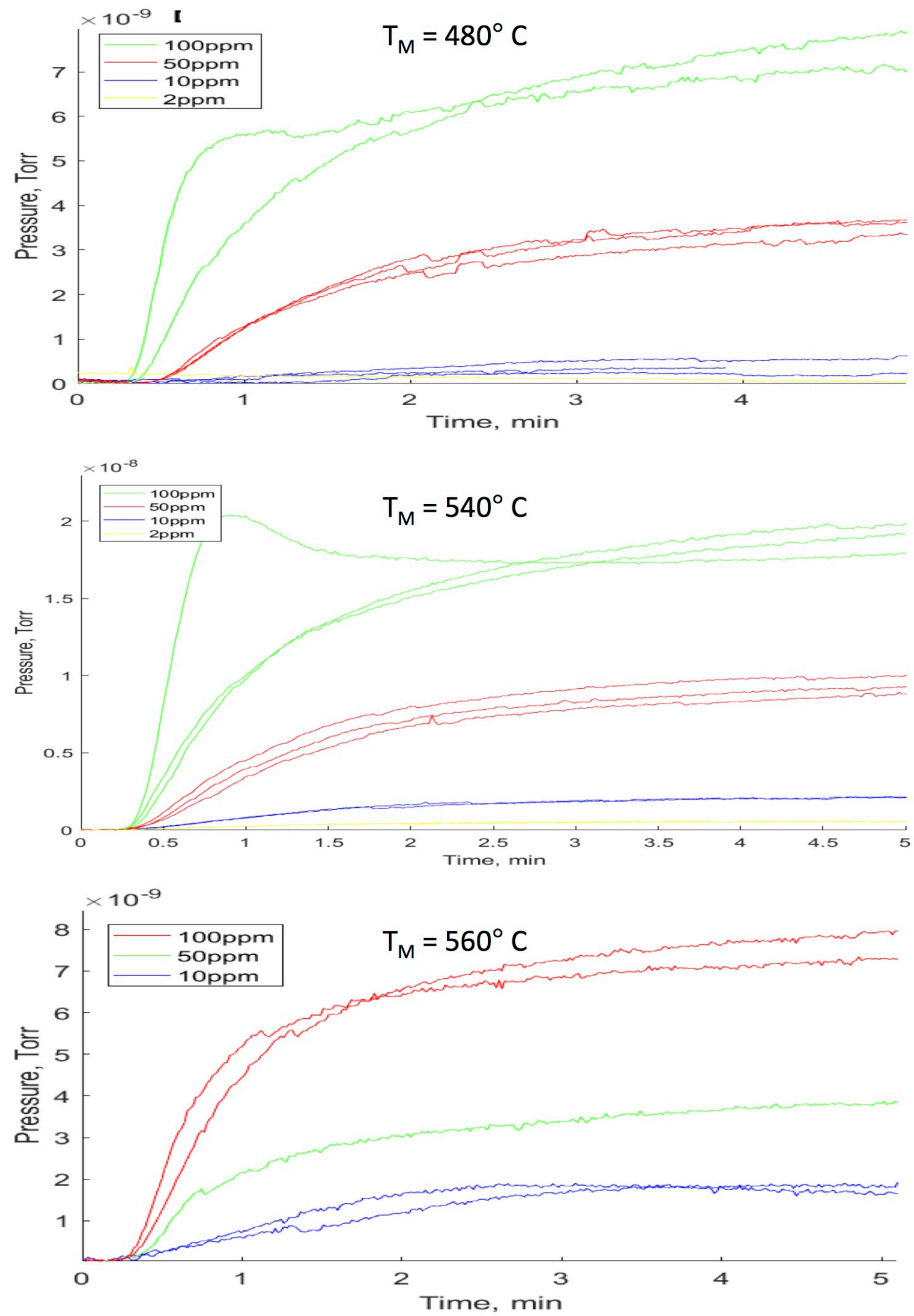


Figure 35. Pressure of prototype #2 to H_2 concentrations at different membrane temperatures.

7.3.3 Equilibrium Mode

An alternative mode, equilibrium mode, can also be used to determine the hydrogen concentration, and then is correlated to the size of steam/water leak of a SHSG. Equilibrium mode is conducted by isolating the ion pump. The ionization gauge gives a measurement of hydrogen pressure, which represents the hydrogen partial pressure in cover gas or the hydrogen concentration in sodium. Figure 36 shows the pressure changes of the prototype #2 for different hydrogen concentrations under equilibrium mode. This mode offers better sensitivity and consistency, but takes a much longer time to reach to determine the hydrogen concentration, i.e. taking longer time to determine hydrogen concentration.

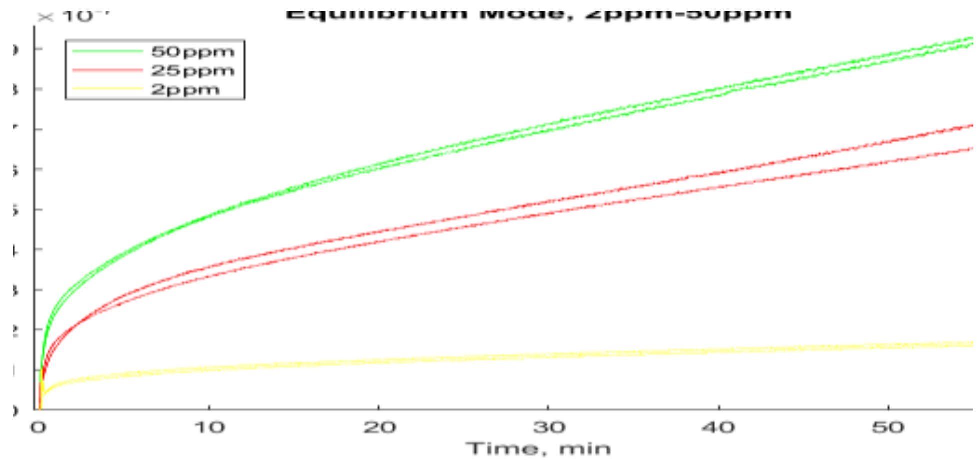


Figure 36. Pressure changes for different hydrogen concentrations under equilibrium mode.

The test results clearly show that the dynamic mode reaches an equilibrium state much faster than the equilibrium mode but with much smaller magnitude. The difference in magnitude depends on the effective pumping speed. In addition, the slope of the equilibrium curve gives a direct measure of the amount of hydrogen diffusing into the vacuum chamber, which in turn gives a direct measurement of hydrogen pressure in the sodium flowing across the nickel membrane. Both operational modes, if calibrated, can provide direct measurements of hydrogen concentration or pressure. Both prototypes have demonstrated a detection sensitivity of hydrogen concentration down to 2 ppm. If mixing gas is flowing into a vacuum vessel, the response time is ~ 1 sec for any hydrogen concentrations. If mixing gas is flowing into a vessel with argon cover gas, the response time is ~ 1 sec or longer, depending on flow rate, hydrogen concentration, and vessel dimension.

8 DIFFUSION-TYPE IN-SODIUM HYDROGEN METER

The hydrogen meter leak detector (HMLD) system of the EBR-II provides a means of detecting the onset of a water-to-sodium leak so corrective action can be taken before major damage occurs to the secondary system. Three different types of diffusion-type ISHMs were designed and implemented in the HMLD system. The system consists of twelve HMLDs, including six original design of HMLD, five Fast Response Freezable HMLDs (FRFHMLDs), and a Compact Hydrogen Meter (CHMLD) [9]. To avoid potential sodium flow disruption by HMDL and flow damage to it, a flow by-pass arrangement is recommended.

A compact diffusion-type in-sodium hydrogen meter (ISHM), based on the design of the CHMDL used for the Fast Flux Test Facility (FFTF), is proposed for hydrogen detection of steam-to-sodium leaks of a SG of a SFR. The compact ISHM is designed for fast response, inexpensive, simplicity, sensitive, and seismic ruggedness. A compact ISHM consists of five major modules, a compact nickel membrane probe assembly, a vacuum manifold and hydrogen measuring system, a sodium hydroxide injection assembly, a leak analyzer, and a control and display module. It has no sodium pump, valves, and flowmeter and is mechanically supported by the sodium line to which it is closely coupled. This section documents the detailed design of ISHM, the fabrication of ISHM prototypes, and the construction of an in-sodium test apparatus.

8.1 Leak Detection System Requirements

Diffusion-type ISHMs aim at detecting small leaks in time to prevent wastage propagation to adjacent tubes and will be placed in the sodium inlet and outlet pipelines of each SG. Important meter design parameters are its response time, detection sensitivity, and performance reliability. Similar to a CGHM, output of an ISHM is either the ion pump current or an ionization gauge reading. Both reflect the hydrogen flux diffusing through the nickel membrane. Therefore, as described in Section 5.1, the sensitivity of the hydrogen meter is proportional to A/x, where A is the surface area of the membrane and x is the thickness of the membrane while the response time is directly proportional to x^2 and sensor distance from the leak.

<u>Detection Time</u>

Detection time of an ISHM is generally determined by:

- Time required for a leak to be detectable: Once a leak is initiated, sometime may elapse before the leak develops to a magnitude that is well above the background hydrogen level and can be positively detected by an ISHM. This required time is therefore dependent on the leak rate and the detector sensitivity.
- Transport time of reaction products, mainly hydrogen, from the location of the leak to the detector: This transport time depends on the distance from a detector to the leak location and on the sodium flow rate.
- Response time of an ISHM: The response time of an ISHM is controlled primarily by the diffusion-membrane design. In general, the hydrogen diffusion time is inversely proportional to membrane thickness, membrane operating temperature, and hydrogen pressure differential across the membrane.

<u>Detection Sensitivity</u>

It must be recognized that there is a background hydrogen concentration in the sodium system. For example, the typical partial pressure of hydrogen in the cover gas of EBR-II secondary sodium system at full power appears to range from 1 to 1.5 x 10^{-3} Torr, or 1 to 1.6 vppm at a total pressure of 18.1 psia. The hydrogen concentration in the secondary sodium at full power is typically about 100 ppb by weight.

Therefore, the detection sensitivity must be better than the lower limits of the backgrounds. For example, the measurement requirements of the hydrogen meters proposed for MONJU FBR are 0.045 to 10 ppm in the sodium and 1 to 1,000 ppm in the cover gas.

Performance Reliability

The hydrogen concentration in sodium is reflected either from the ion-pump current or the ionization gauge reading. Hence, the meter performance consistency is intimately related to the ion pump and ionization gauge performances. Overall, the meter performance is affected by the changes of (1) membrane permeability, (2) surface conditions of the ion-pump cathode plate, (3) surface outgassing of the vacuum chamber, and (4) operating temperature of the meter. To ensure the meter performance, frequent meter calibration is needed.

8.2 Design of ISHM

A compact ISHM consists of five major modules, a compact nickel membrane probe assembly, a vacuum manifold and hydrogen measuring system, a sodium hydroxide injection assembly, a leak analyzer, and a control and display module.

8.1.1 Compact Nickel Membrane Probe Assembly

The compact nickel membrane probe assembly consists of six major components:

- Nickel membrane probe,
- Membrane jacket,
- Probe nozzle,
- Sodium transferring coil-tubing,
- Sodium chamber, and
- Vacuum feedthrough.

Figure 37 shows 3D illustrations of the compact nickel membrane probe assembly of the proposed compact ISHM. Because of its many components and its complexity, a membrane probe assembly needs to be assembled in a specific sequence. To deploy for use, for prompt leak detection, the assembly is welded onto the sodium transporting line at a location close to the inlet or outlet of SG. An isolation valve is then welded at the end of the assembly and leads through a vacuum manifold and hydrogen measuring system.

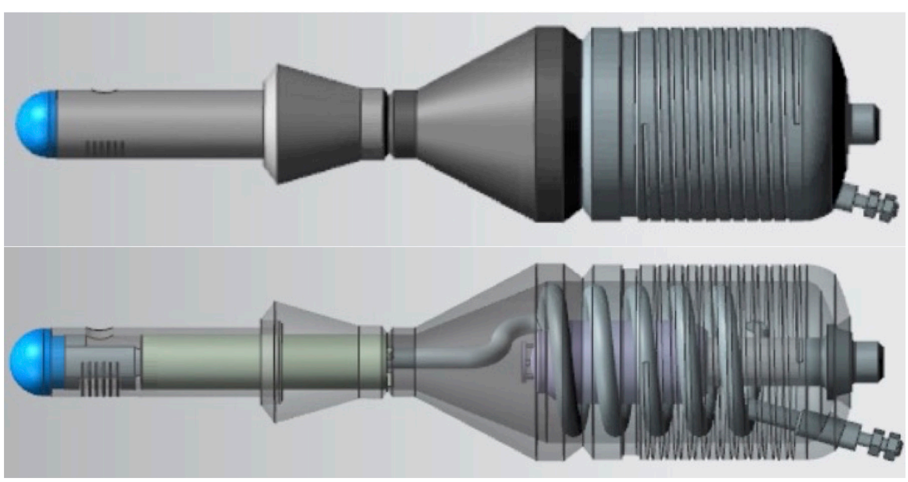


Figure 37. 3D illustrations of compact nickel membrane probe assembly.

Figure 38 shows the detailed design and physical arrangement of compact nickel membrane probe assembly. To avoid hydrogen trapping inside the assembly, it should be mounted upside-down in the sodium transport piping. The red arrows indicate the sodium flow directions. The probe nozzle protrudes ~73 mm (2.875 in.) into the main sodium line being sampled and creates a pressure drop that drives a sample sodium flow through the probe assembly, eliminating the need for a pump, such as an EM sodium pump used for original HMLD of EBR-II.

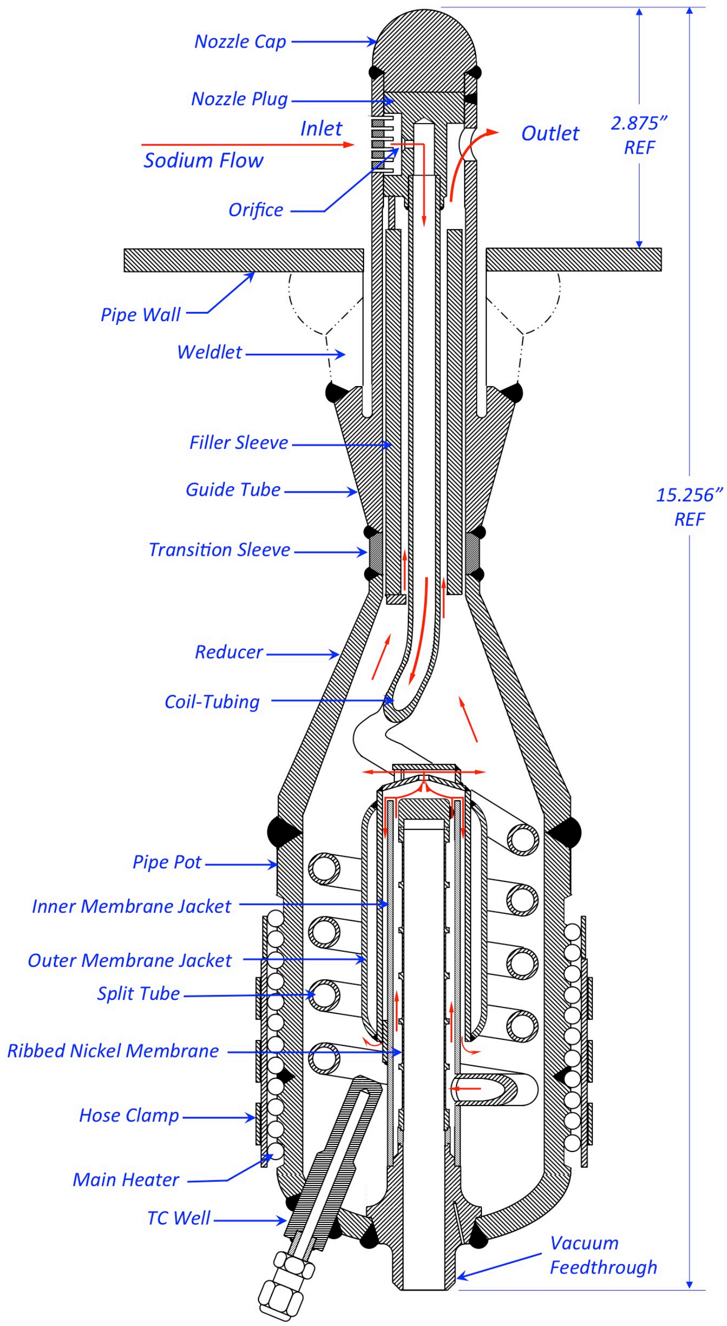


Figure 38. Assembly of compact nickel membrane probe assembly.

An orifice is placed in the inlet of the probe nozzle to regulate the sodium flow rate and an inlet grille slots (~0.8 mm wide) screens out any entrained particles too large to pass through the orifice. The sample sodium flows downward to the sensor through a helical coil-tubing into the membrane inner jacket. During the circulation (~3 sec) the sodium flow is heated to 482°C (900°F), with some of the heat provided by regenerative exchange from the warmer sodium outside the coil-tubing. The sodium flows upward along the ribbed membrane, and then circulates to the membrane outer jacket. At the top of the ribbed membrane, about 10% of the sodium flow escapes upward through a small hole, along with any gas bubbles present. The remainder flows inside the outer jacket back to the bottom of the membrane. The outer jacket is double-walled with the annulus evacuated to provide thermal insulation, so that the sodium around the membrane remains nearly isothermal at 482°C. The flow then rises slowly through the POT and rejoins the sodium flow escaped from the outer jacket and exits the probe nozzle to the main sodium stream. The POT and the sodium in it constitute a large thermal mass, which has been shown to dampen effectively the rise in membrane temperature that would otherwise result from a sudden drop in main sodium line. To maintain the sodium in the POT at an isothermal temperature (482°C), a heater is tightly wound on a lathe onto the POT wall and clamped for good thermal contact.

The pressure boundary material of construction of the membrane probe assembly shall meet the requirements of Section III of the ASME B&PV Code for Class 2 vessels including the requirements of ANSI/ ASME NQA-1. For welding compatibility and operating temperature, the material shall be Type 304, 304H, or 316H stainless steel or Croloy depending on the material of the SG piping.

Nickel Membrane Probe

The design of ribbed membrane was selected. The tubular seamless nickel membrane is made of Nickel–201 (ASTM B-161). Nickel–201 is a pure nickel (99%) with low carbon (< 0.02%), a preferred nickel for high temperature (> 320°C) applications. Before machining, the membrane has an OD of 15.875 mm (5/8 in.), ID of 12.7 mm (0.5 in.), and length of 95.25 mm (3.75 in.) Its wall thickness is milled down to 0.254 mm (10 mil) with five ribs separated evenly (~12.5 mm) giving a total active surface of 30.53 cm^2 (4.73 in^2) for hydrogen diffusion and a volume of 9.69 cm^3 (0.59 in^3). Figure 5 shows a fabricated nickel membrane probe. It is recommended that, after machining and welding, the nickel membrane receives low carbon stress relieve treatment at 400°C. The probe is then welded to a transition sleeve that leads to the inlet for the vacuum feedthrough and a cap is welded on the other end. Three weld-buttons were welded on the probe cap with equal spaces to guide the slide-fit during assembly and to prevent vibration while the ISHM is in operation.

Membrane Jacket

The sample sodium flows through two layers of membrane jacket, inner and outer. The outer jacket has three equally spaced dress-plates welded at the open end of the jacket such that it can slide fit over the inner jacket. Three weld-buttons are welded at one end of the inner jacket with equal spaces to guide the slide-fit during assembly and to prevent vibration while the meter is in operation. Once the inner jacket is slid in at the designated depth, the three dress-plates will then be welded onto the inner jacket. The other end of the inner jacket is welded on the inlet side of the vacuum feedthrough to provide support and to form a flow pathway.

The sodium stream flows upward along the ribbed membrane, and then circulates to the membrane outer jacket. At the top of the ribbed membrane, about 10% of the sodium flow escapes upward through a small hole, along with any gas bubbles present. The remainder flows inside the outer jacket back to the bottom of the membrane. The outer jacket is double-walled with the annulus evacuated to provide thermal insulation, so that the sodium around the membrane remains nearly isothermal at 482°C.

Vacuum Feedthrough

The vacuum feedthrough has a membrane probe welded on its inlet to seal and support the membrane probe and to provide vacuum later. The membrane jack is then slid over the membrane probe and welded on the inlet to provide support of the jacket and to form a flow pathway. The outlet end of the feedthrough will be welded to the vacuum line connected to a vacuum manifold and hydrogen measuring system.

Probe Nozzle

The probe nozzle consists of a nozzle guide tube, a nozzle cap, a nozzle plug, and a nozzle filler sleeve. It protrudes into the sodium stream being sampled and creates a pressure drop that drives a sample sodium flow through the probe assembly. The pressure drop varies as the square of the flow velocity past the nozzle. An orifice at the inlet (upstream) side of the nozzle is sized to allow for a stable sodium flow bypassing through the meter at full flow rate in the line being sampled. The calculation of the diameter of the orifice is presented in Appendix A. An inlet grille with 0.032-inch-wide slots screens out any entrained particles too large to pass through the orifice. The sample stream flows downward to the ribbed membrane through a helical coil tubing.

Sodium Transferring Coil-Tubing

The sample sodium flow is transferred from the probe nozzle through a helical coil tubing to the ribbed membrane. The straight end is welded at the outlet of the nozzle plug and the coiled end is welded at the inlet of the membrane inner jacket. The temperature of the sample sodium flow at the SG outlet is 322°C. Before flowing into the membrane inner jacket, the sample sodium flow is heated to 482°C (900°F) while passing the coiled region of the coil tubing.

Sodium Chamber

The sodium chamber consists of a reducer, a “POT”, and a thermocouple (TC) well. The standard 3”-to-1” reducer (Schedule 80) couples the probe nozzle to the POT to form a sodium chamber. The POT is formed from a standard 3 in. pipe (Schedule 80) and butt-welded with an end cap, thus matching the containment integrity of the SG sodium piping. The wall of the POT is reduced to Schedule 40 thickness at the bottom of a helical groove into which the main ISHM heater is tightly wound on a lathe and clamped for good thermal contact. The chamber and the sodium in it constitute a large thermal mass, which should effectively damp the rise in membrane temperature that would otherwise result from a sudden drop in main sodium line. A welding port (1.255 in. in diameter) is drilled at the center of the end cap and in which the nickel membrane probe welded on a vacuum feedthrough will then be inserted. After the completion of the ISHM assembly, the POT and the vacuum feedthrough will be welded to seal the POT. A TC well (12.7 mm OD) is inserted into the end cap with 24-degree angle and touch the top of the coil-tubing for monitoring the temperature of the sodium flow and controlling the main ISHM heater.

8.1.2 Vacuum Manifold and Hydrogen Measuring System

Basically, the vacuum manifold and hydrogen measuring system is the same as the one used for CGHM, consisting of a vacuum line, an isolation valve, an ion pump, an ionization gauge, a roughing valve, and a roughing pump. Figure 39 shows the layout of the system. Required meter components, such as ion pump and ionization gauge, are selected and described. The compact ISHM assembly module is located inside the SG containment but instruments could be located outside the SG containment if necessary. The system provides pressure and current of ionization gauge to the leak analyzer for leak and leak changing rate analysis.

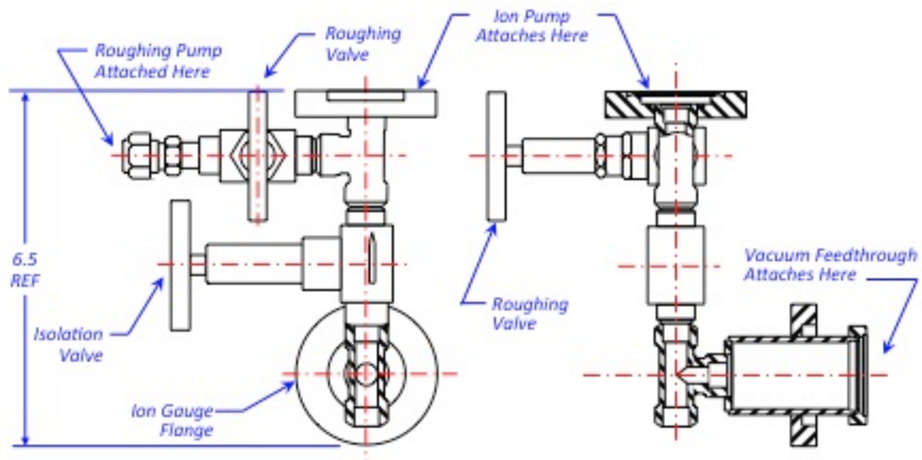


Figure 39. Layout of vacuum manifold and hydrogen measuring system

As the design of CGHM, it is recommend that an additional valve, called ISHM assembly isolation valve, is placed in the vacuum line between the vacuum feedthrough and the system, so that frozen sodium in the POT would have a closed valve as a second barrier during any maintenance that involves opening of the vacuum manifold. The ISHM assembly isolation valve then would be ready and useful to seal the assembly for leak testing.

Rough Pumping System

Vacuum platform and rough pumping system are commercially available and can be modified to accept a simulated hydrogen meter stack. Rough pumping is accomplished with a Pfeiffer TurboMolecular pump and a Varian 4-stage, diaphragm pump. All pump stages are of an oil-free design to ensure there is no potential for contamination of a prototype hydrogen meter. When in use, the vacuum platform will be used to bake out and establish the initial internal vacuum of the compact ISHM. Additionally, the platform will provide a vacuum environment for testing the compact ISHM response to ppm levels of hydrogen gas in argon. Pressure is measured by monitoring ion pump current of an ionization gauge.

After a compact ISHM is assembled and leak tested, its vacuum manifold is evacuated by the rough pumping system and baked out at 177-205°C (350-400°F) for at least a day for outgassing of the inner surfaces of the vacuum manifold system and the membrane probe. Once the outgassing drops to a low rate, the system is isolated from the ISHM by closing the roughing valve and the ion pump is then started up. From then on, the ion pump should run continuously, whether the compact ISHM is in operation or in service. Usually a compact ISHM would be vacuum tight and does not need to be re-evacuated by a rough pumping system.

Ion Pump

For the present application, an ion getter pump will be adequate and the getter material is titanium. An ion pump with at least an eight liter per second pump speed will be sufficient for the proposed probe design. An Agilent™ 10 l/s VacIon pump, shown in Figure 40, was identified and used for CGHM. The pump provides the highest pumping speed (10 liters per second) and capacity for hydrogen that are sufficient for the proposed ISHM design. Table 8 lists the technical specifications of the Agilent™ pump. The pump is essentially an ionization device. Hydrogen molecules are bombarded by high-energy electrons and turned into positively charged ions. Under the influence of a strong electric field and a magnetic field, the ions are accelerated into the titanium cathode. The pressure reading is directly proportional to pump current. The predicted lifetime of an ion pump is based on pumping air or nitrogen at 10^{-6} torr [10]. When pumping hydrogen, the true pressure is approximately three times the gauge reading, which tends to reduce the pump life accordingly. The ion pump has a finite lifetime that depends on the average hydrogen concentration being monitored.

Figure 40. Agilent 10 l/s VacIon pump.

Table 8: Technical specifications of Agilent™ 10 l/s VacIon pump

Specification	Value
Element	Diode
Nominal pumping Speed for Nitrogen	10 l/s
Operating Life at 1X 10^{-6} mbar	40,000 hours
Maximum operating voltage	+7,000 Vdc
Maximum starting pressure	$\leq 1 \times 10^{-4}$ mbar
Ultimate pressure	$< 10^{-11}$ mbar
Internal volume	0.4 liters
Maximum baking temperature	350°C
Temperature limits: Pump Magnet	400°C 300°C

Ionization Gauge

Selection of a proper ionization gauge must consider the operating temperature because of a relatively higher temperature during bakeout. An Agilent™ UHV-24 nude ionization gauge, for example, satisfies the requirements and has been selected for use on the hydrogen meter stack. The gauge contains three major elements:

- Filament – The filament serves as a source of electrons.
- Grid – The grid functions as the electron collector operating at a positive potential (typically +150 V) with respect to the filament.
- Collector wire – Along the center of the cylindrical grid structure is a very small diameter ion collector wire operating at a negative potential (typically 28 V) with respect to the filament.

Figure 41 shows the UHV-24 nude ionization gauge. The positive ions produced on the inside of the grid structure are accelerated toward and are neutralized at the collector by electrons from the external circuit. The number of ions produced per electron is proportional to gas density, and the positive ion current to the ion collector is used as an indication of pressure. Thus, for a constant value of accelerating voltage in excess of the ionization potential of the gas, the number of positive ions formed should vary linearly with pressure and with electron current [11]. Thus, ionization gauges have different relative sensitivities for different gases and the gauge controller must correct its sensitivity to reflect the gas composition and pressure.

The UHV-24 nude ionization gauge, with an x-ray limit of 2×10^{-11} Torr, provides reliable pressure measurement from 1 mTorr down to 2×10^{-10} Torr, with reduced performance at pressures lower than 2×10^{-10} Torr [11]. The gauge is designed with replaceable dual Thoria/Iridium filament assemblies on a 2-3/4" Conflat flange and bake-out temperature up to 450°C. Nude gauges are recommended for bakeable, all metal, ultra-high vacuum systems where maximum exposure to the vacuum gives the highest possible accuracy. Table 9 lists its technical specifications of UHV-24 nude ionization gauge and Table 9 gives the relative sensitivities of certain common gases.

Figure 41. Agilent™ UHV-24 nude ionization gauge.

Table 9: Technical specifications of Agilent™ UHV-24 nude ionization gauge

Specification	Value
Operating pressure	2×10^{-11} to 10^{-3} Torr
Nominal sensitivity for N_2	25/Torr
Sensitivity for H_2 versus N_2	0.42
Emission Current:	4 mA for range 5×10^{-10} to 10^{-4} Torr 10 mA for < 5×10^{-10} Torr ≤ 0.1 mA for pressure > 1×10^{-4} Torr
Bake-out temperature	450°C
Additional features	Replaceable Thoria-coated Iridium or dual tungsten filament

Table 10: Average ionization gauge sensitivity ratios for various gases normalized to nitrogen

Gas	He	Ar	H_2	N_2	O_2	Dry air	CO	CO_2
Sensitivity Ratio	0.13	1.47	0.42	1.00	0.77	0.90	1.01	1.09

Gauge Controller

An XGS-600™ Gauge Controller, shown in Figure 42, has been acquired for the control of the Agilent™ UHV-24 nude ionization gauge for the development of the CGHM. In the present application, multiple DTHMs would be implemented, i.e. multiple ionization gauges would be used. The gauge controller is capable of viewing up to 8 gauges on one screen and can employ as many as 5 ionization gauges or 12 convection gauges in one unit with its simple user interface [12]. Since ionization gauges have different relative sensitivities for different gases, the gauge controller is capable of correcting its sensitivity to reflect the gas composition and pressure.

Figure 42. Agilent™ XGS-600 gauge controller.

8.1.3 Sodium Hydroxide Injection Assembly

For performance evaluation of compact ISHM, a sodium hydroxide (NaOH) injection assembly, shown in Figure 43, is designed and fabricated. The injection assembly injects designated amount (mg range) of NaOH into the molten sodium into an expansion tank, which is covered with argon gas at all time. Sodium hydroxide then reacts with the molten sodium to produce hydrogen before flowing into the ISHM prototype. Sodium hydroxide is one of the principal reaction products of SWR. For performance evaluation and *in-situ* calibration, NaOH is used, instead of injecting steam into molten sodium, to avoid the wastage that would occur at the injector head. The injection assembly consists of two injection tubes (1/2" in diameter), a NaOH loading tube (1/4" in diameter), a pushing rod (1/8" in diameter), a tee and a cross, and three ball valves. A tee links the two injection tubes together. An injection valve is connected to the end of the second injection tube. When loading of NaOH, the injection assembly and the sealed NaOH pellet are placed inside a glove bag, which is purged with argon gas. The front injection tube is first connected to the injection valve. The injection tubes are vacuumed and then purged with argon gas. After a designated amount of NaOH is loaded into the front end of the loading tube, the pushing rod is inserted inside the loading tube. The loading tube is then inserted inside the injection tube, and pushed through the injection valve into the expansion tank. By pushing the push rod all the way into the loading rod, the NaOH pellet then can be dropped into the molten sodium.

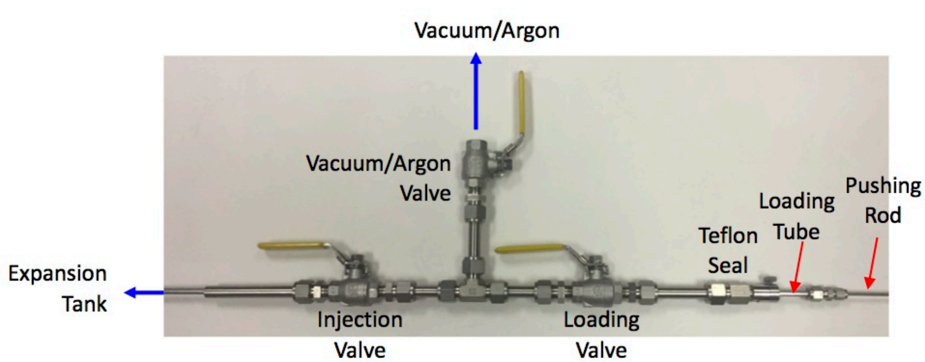


Figure 43. Sodium hydroxide injection assembly.

8.1.4 Leak Analyzer

Hydrogen concentration in sodium typically varies between 100 ppb during shutdown and 150-200 ppb at full reactor power, depending on cold trap operating practice. These changes occur slowly, not exceeding 0.02 ppb/min in EBR-II, for example. At any background level, a steam leak into the sodium is detected as a faster- than-normal rate of rise in hydrogen concentration. The hydrogen concentration and partial pressure in the sodium is reflected from either the ion-pump current or the ionization gauge reading. Both reflect the hydrogen flux diffusing through the membrane. Hence, the meter performance consistency is intimately related to the ion pump and ionization gauge performances. Overall, the meter performance is affected by the changes of (1) membrane permeability, (2) surface conditions of the ion-pump cathode plate, (3) surface outgassing of the vacuum chamber, and (4) operating temperature of the meter.

The leak analyzer consists of a data acquisition (DAQ) system and a computer:

- DAQ system – Inputs to the system includes sensor temperature, ion-pump current, and ion-gauge current.
- Computer – Control software will be developed to provide (1) real-time hydrogen concentration/pressure/leak rate outputs, (2) meter operation control, and (3) meter calibration control.

8.1.5 Control and Display Module

The control and display (C&D) module, similar to the one used for the performance evaluation of CGHM, is used to operate the pilot test facility and to display leak rate and some critical operation information. Two sets of data are measured and transferred from the computer to the module. One set includes pressure change and pressure changing rate, which can be correlated to water-leak rate and water-leak changing rate, respectively. Table 11 summarizes the control variables and their settings of ISHM pilot test.

Table 11: List of control variables and settings of ISHM

Device	Variable	Setting	Remark
Ion Gauge TC	Temperature (T_{IG})	450°C	For bakeout
Membrane TC	Temperature (T_M)	370 - 560°C (typical 480°C)	Heat up the membrane gradually to the operating temperature
Roughing Pump	Pressure (P_{RP})	$< 10^{-4}$ mbar	Shut off when ionization pump kicks on ($P_{RP} < 10^{-4}$ mbar)
Ion Pump	Current (I_{IP})	(Undecided)	Ion Pump Controller converts P_{IP} to I_{IP} (device dependent)
	Pressure (P_{IP})	$< 10^{-11}$ mbar	Kick on when $P_{RP} < 10^{-4}$ mbar
Ionization Gauge	Current (I_{IG})	(Calibration)	Ionization Gauge Controller converts P_{IG} to I_{IG} (device dependent)

8.3 Experimental Test Apparatus of ISHM Prototypes

For in-sodium test of diffusion-type ISHM prototypes, a test apparatus has been designed and constructed. The test apparatus is being integrated into the USV experiment facility for performance evaluation of ISHM prototypes. Figure 44 illustrates the ISHM experiment apparatus. The apparatus consists of a compact ISHM assembly, a sodium loop, a NaOH injection assembly, a vacuum manifold and hydrogen-measuring module, a heating control and temperature monitoring module, and a data acquisition and leak analyzer unit. Figure 45 shows a photo of the fully assembled test apparatus being integrated onto the USV sodium circulating loop.

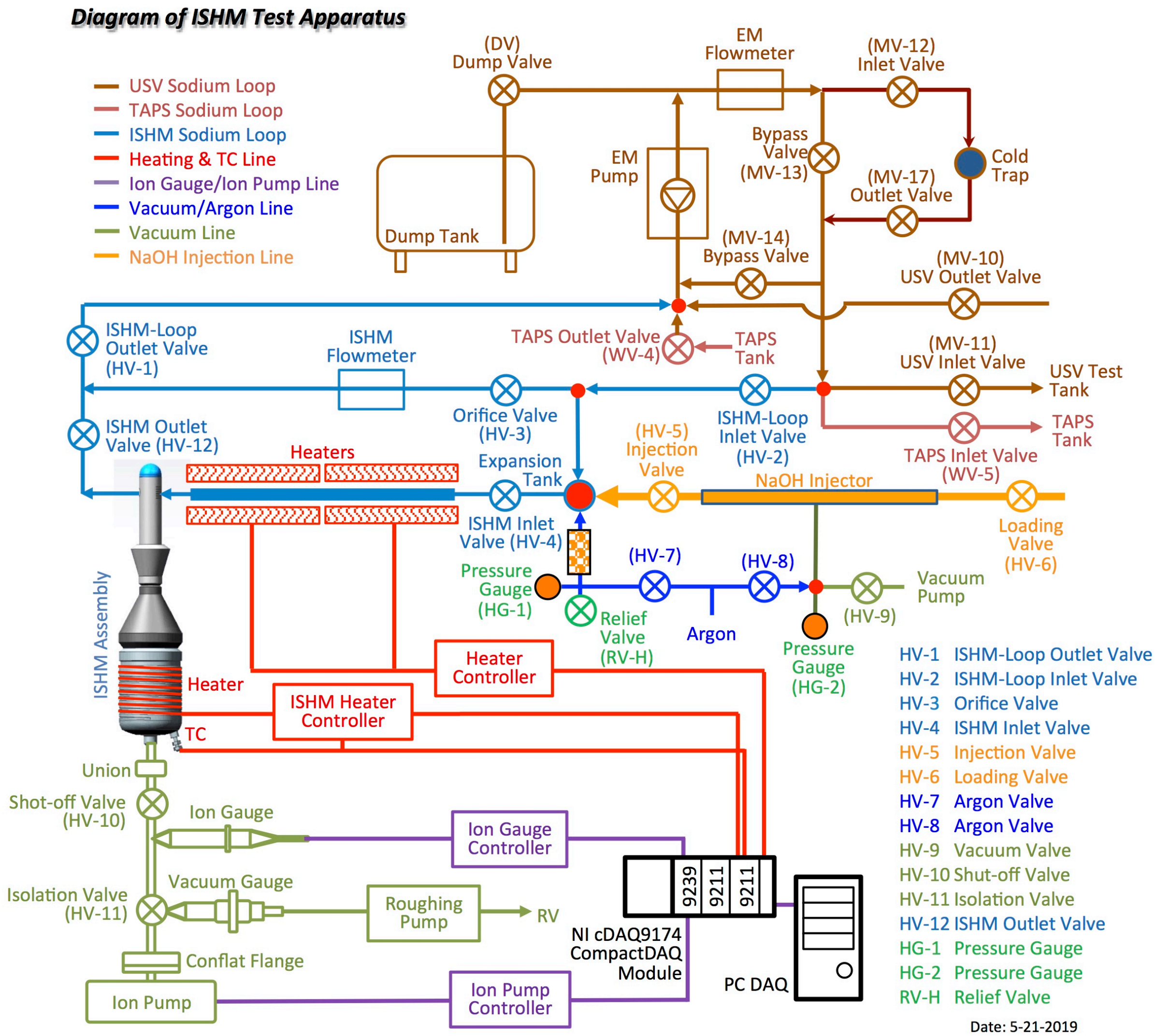


Figure 44. Diagram of the test apparatus for performance evaluation of ISHM prototype.

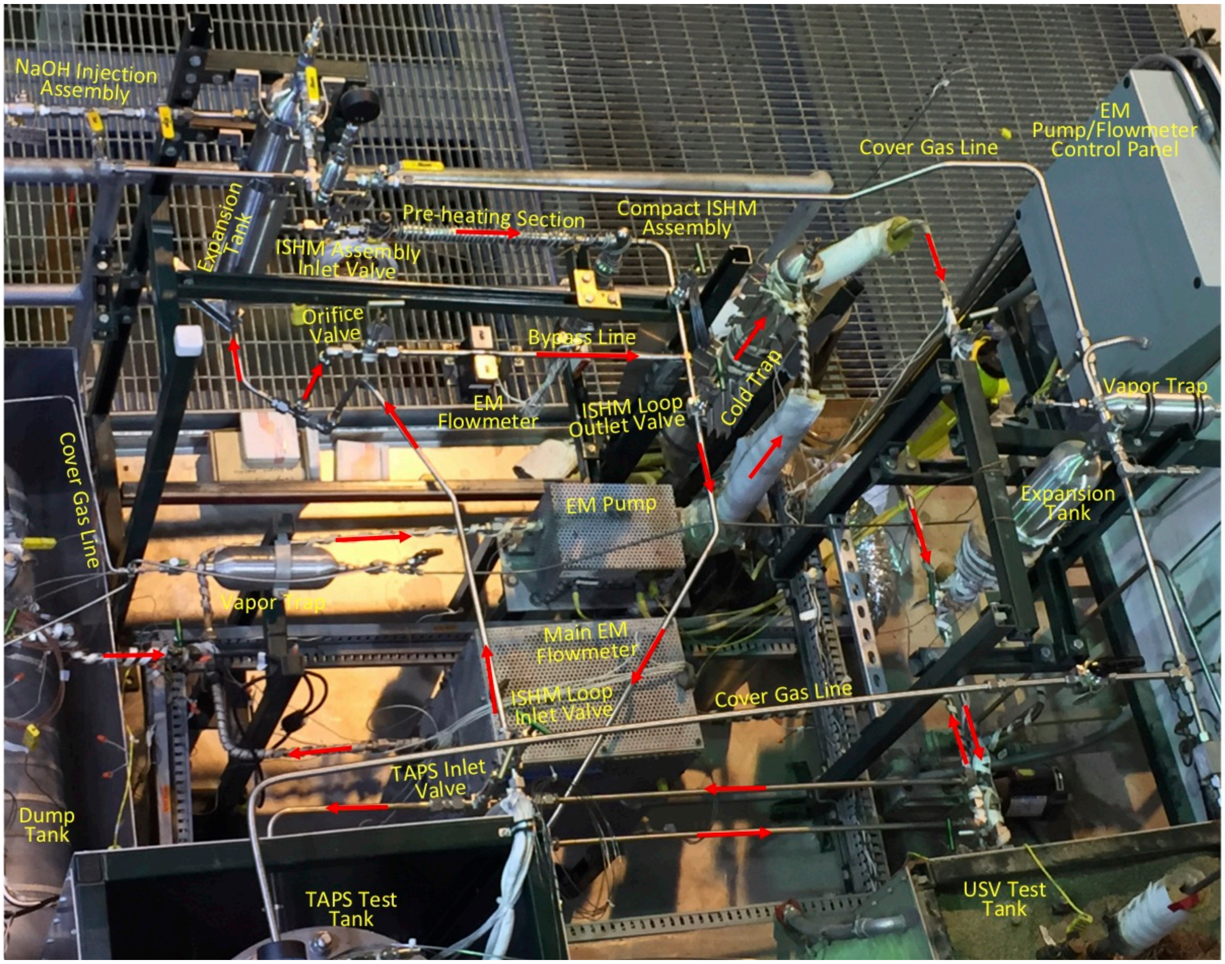


Figure 45. Photo of the fully assembled compact ISHM test apparatus.

The sodium transferring pipelines of the test apparatus are made of stainless steel (SS) tubes with 0.5” in diameter and are kept at 150°C during normal operation. The compact ISHM assembly is mounted upside-down in the loop after a pre-heating section. To reduce the heating load of the external heater of the compact ISHM assembly, the pre-heating section, which is 1” in diameter, would heat the sodium from 150°C up to 480°C. The test apparatus can be isolated from the USV sodium circulation loop by shutting off the two high-temperature isolation valves. The ISHM sodium loop consists of a bypass pipeline and an ISHM testing pipeline. A high-temperature orifice valve is used to control the sodium flowrate into the compact ISHM assembly. The assembly is leak checked and is heated by an external heater wrapped around it to maintain the nickel membrane in the ISHM assembly at a designated isothermal temperature. The operating flowrate of the assembly is limited by an orifice nozzle at its inlet at 0.3 gallon/min (GPM). An ISHM inlet valve is mounted at the inlet of the pre-heating section to isolate the assembly from the ISHM sodium loop if needed. A compact EM flowmeter is installed along the bypass pipeline to monitor the flowrate of the bypassed sodium. An ion pump and an ionization gauge are mounted on the vacuum feedthrough at the end of the ISHM assembly and are used to measure the amount of hydrogen that diffuses though the high-temperature nickel membrane in either equilibrium or dynamic modes. The hydrogen pressure is an indicator of the hydrogen concentration in molten sodium, which can be then correlated to the water leak of a steam generator.

9 DISCUSSIONS AND CONCLUSIONS

This section summarizes the development and demonstration of the diffusion-type CGHM and ISHM in FY19. The R&D efforts have been focused on (a) creep-collapse tests of different designs of nickel membrane probes, (b) performance evaluation of CGHM prototypes, (c) fabrication of ISHM prototypes, and (d) construction of a test apparatus for in-sodium performance evaluation of compact ISHM prototypes.

A creep-collapse test apparatus was designed and constructed. Ten straight nickel membrane probes and two ribbed nickel membrane probes were fabricated and tested. Eight straight nickel membrane probes are with original designs of cap and collar. Four have wall thickness of 10 mils and four have wall thickness of 14 mils. The eight membrane probes were tested at temperatures of 600°C at different pressure ranges from 100 to 1,000 psig. All probes failed but one. Two straight nickel membrane probes (10 mil) with bullet cap and collar were then fabricated and tested. It appeared that the new designs prolong the surviving time of the membrane probes. Two ribbed membrane probes with thickness of 10 mil were also fabricated and tested. They showed further improvement in survival time. However, their failure mechanism is different, one buckled in an axial direction and the other collapsed in a radial direction. The ribbed tubular nickel membranes were milled down to the designated membrane thickness (10 mil) from an extruded nickel tube with 1/16" in thickness. All the nickel membranes were inspected after receipt. Several nickel membrane probes have score marks along the length-direction either caused by the extrusion process or milling. It is a concern that the scoring and stress concentration generated by machining could have caused the membrane probes to collapse too fast. Based on the test results, the life expectancy of the nickel membranes cannot be predicted at this time. It is also inconclusive, if the membrane's strength weakening is caused by either the welding process, imperfection of the membranes, grain size/boundary at high temperature, or other reasons. It is recommended that nickel membranes be heat-treated at 1,300-1,500°F in an inert gas environment to remove stresses introduced into the material during extruding, milling, and welding processes. In addition, surface analysis of the membranes before and after the creep-collapse test is needed to study creep-collapse phenomena, grain size and boundary at high temperature, welding process, and quality of nickel membranes. Rather than extrusion and milling, the 3D printing technology could be an alternative method to fabricate both straight and ribbed nickel membranes. The technology could reduce residual stresses due to machining and cost, as well as improve machining accuracy.

A test apparatus for performance evaluation of CGHM prototypes was designed and constructed. Two CGHM prototypes have been fabricated and tested. These two CGHM prototypes have demonstrated a sensitivity of detecting hydrogen concentration to 2 ppm in argon cover gas, as required by the performance specification. The test results clearly show that the dynamic mode reaches an equilibrium state much faster than the equilibrium mode but with much smaller magnitude. In addition, the slope of the equilibrium curve gives a direct measure of the amount of hydrogen diffusing into the vacuum chamber per unit time, which in turn gives a direct measurement of hydrogen pressure in the cover gas. Both operation modes, if calibrated, can provide direct measurements of hydrogen concentration (pressure). Both modes show hydrogen detection sensitivity down to 2 ppm or less. Under dynamic mode, the CGHM prototype has a response time around 1 sec. The equilibrium shows better consistency but with much longer response time, i.e. to approach pressure equilibrium between inside and outside of the membrane.

The design of a diffusion-type ISHM aims for fast response, low cost, simplicity, increased sensitivity, and seismic ruggedness. After evaluation of the different types of DTHM, a compact ISHM is proposed for hydrogen detection of steam-to-sodium leaks of SGs. The compact ISHM consists of five major modules, a compact nickel membrane probe assembly, a vacuum manifold and hydrogen measuring system, a sodium hydroxide injection assembly, a leak analyzer, and a control and display module. It has no sodium pump, valves, and flowmeter and is mechanically supported by the sodium line to which it is closely coupled. The fabrication of the first compact nickel membrane probe assembly is completed and the second one is in progress. The design specifications and operating procedures of the proposed compact diffusion-type

ISHM were identified. The Argonne under-sodium viewing (USV) facility will be used for in-sodium performance evaluation of compact ISHM prototypes. A test apparatus for in-sodium performance evaluation of ISHM prototypes was designed and the fabrication of the apparatus and its integration with the USV facility is in progress. The test apparatus consists of a compact ISHM assembly, a sodium loop, a NaOH injection assembly, a vacuum manifold and hydrogen-measuring module, a heating control and temperature-monitoring module, and a data acquisition and leak analyzer unit. Performance evaluation of the compact ISHM prototypes will be conducted after the construction and integration are complete.

DTHMs can be deployed for monitoring hydrogen concentration in coolants of most of the liquid metal reactors or molten salt reactor, as well as for monitoring hydrogen production, for example, of an Integral Molten Salt Reactor (IMSR) power plant. Hydrogen is one of the main attributes of stress corrosion cracks in stainless steel components/structures, such as reactor piping/tubing or used-fuel storage canisters. To avoid SCC and prolong life expectancy, DTHMs can be used to monitor trace amount of hydrogen in different reactors or storage canisters under harsh condition (including high temperature, high radiation, or high corrosive). With ppb sensitivity and fast response time, DTHM can also be used to monitor or capture deuterium and tritium or to be an in-process, near real-time sensing technology to track tritium production.

10 FUTURE WORKS

Argonne will continue the development and evaluation of both CGHM and ISHM for SGLDS of SFRs. The following tasks are proposed:

Creep-collapse Test

- Complete creep-collapse tests of the two additional ribbed membrane probes;
- Conduct analysis of each probe tested and to estimate the life expectancy of the nickel membranes of different wall thicknesses;
- Complete strain/displacement tests of ribbed nickel membrane

Development of diffusion-type CGHM

- Complete performance evaluation of ISHM prototypes to
    - Determine the sensitivity, response time, and reproducibility,
    - Determine the calibration requirements and procedure,
    - Determine the optimal meter operating conditions.

Development of diffusion-type ISHM

- Complete the fabrication of the 2nd compact ISHM prototype;
- Complete the construction of the test apparatus and its integration with the USV sodium test facility for in-sodium test of compact ISHM prototypes;
- Complete the test run of the test apparatus;
- Conduct laboratory pilot testing for performance evaluation under dynamic and equilibrium modes to
    - Determine the sensitivity, response time, and reproducibility,
    - Determine the calibration requirements and procedure,
    - Determine the optimal meter operating conditions.
- Conduct laboratory pilot testing to evaluate and validate the calibration requirements and procedures;
- Evaluate the test results to determine the optimal meter operating conditions;
- Evaluate the possibility of fabricating ribbed nickel membrane using 3D printing technology to reduce residual stresses, material treatment, and cost, as well as improve machining accuracy.

REFERENCES

1. H. T. Chien, S. Bakhtiari, and S. H. Sheen, Unpublished report, 2014.
2. H. T. Chien, S. Bakhtiari and S. H. Sheen, Unpublished report, 2015.
3. H. T. Chien, W. Lawrence, E. R. Koehl, and A. Wang, Unpublished report, 2017.
4. IAEA document "Status of liquid metal cooled fast reactor technology," IAEA-TECDOC-1083, April 1999.
5. C. Latge, "Interaction of Na and materials," IAEA Education &Training Seminar on Fast Reactor Sci. and Tech., CNEA Bariloche, Argentina, October 2012.
6. Y. Chikazawa, "Acoustic Leak Detection System for Sodium-Cooled Reactor Steam Generators Using Delay-And-Sum Beam-Former," *J. of Nuclear Science and Technology*, Vol. 47, No. 1, pp. 103-110, 2010.
7. M. Matsuura, M. Hatori, and M. Ikeda, "Design and modification of steam generator safety system of FBR MONJU," Nuclear Engineering and Design, 237, pp. 1419-1428, 2007.
8. J. M. McKee, M. M. Osterhout, and R. L. Batten, "Use of a Steam Leak Simulator in EBR-II," *Liquid Metal Engineering and Technology*, 25, ICE Publishing, 1984.
9. M. M. Wrightson, K. McKinley, W. E. Ruther, and J. T. Holmes, "EBR-II Water-to-Sodium Leak Detection System," *Int'l Conf. on Liquid Metal Technology in Energy Production*, Champion, Pennsylvania, USA, May 3-6, 1976.
10. 'User Manual of 10 l/sec VacIon Pump, Manual No. 87-900-139-01(A), Agilent Technologies™.
11. "Instruction Manual of UHV-24/UHV-24p Ionization Gauge," Manual No. 699905505, Rev. E, Agilent Technologies™.
12. "Instruction Manual of XGS-600 Gauge Controller," Manual No. 699908400, Rev. B, Agilent Technologies™.

This page intentionally left blank.

APPENDIX A: CALCULATION OF ORIFICE DIAMETERS FOR COMPACT ISHMS

An orifice at the inlet (upstream) side of the nozzle of a compact ISHM needs to be sized to allow a stable sodium flow bypassing through the meter at full flow rate in the line being sampled. However, different installation location of the piping system, the sodium temperature (sodium density), sodium flow rate, and pipe size might be different. Thus, the orifice diameter of the compact ISHM might also be different. The section presents the calculation of orifice diameters for compact ISHMs. The following parameters of the piping system at where a compact ISHM is to be mounted are required:

- Sodium temperature (*Ts* °C),
- Sodium density @ *T*s (ρ g/cm^3),
- Sodium pipe ID (*d* cm), i.e. flow area (*A* cm^2), and
- Sodium flow rate @ full power (Qv m^3/sec *or* Q_m kg/sec).

The below shows, using EBR-II as an example, the orifice diameter calculation of a compact ISHM installed at the SG outlet. Table 12 lists the piping and sodium parameters for orifice diameter calculation.

Table 12: Piping and sodium parameters at SG outlet

Parameter	Unit	Value	Remark
Sodium temperature, T_{Na}	°C	322	At SG outlet
Sodium density, ρ	g/cm^3	0.874	@ 322 °C
Sodium pipe ID, d	cm	38.735	16-in. pipe (ID=15.24 in.)
Flow area, A	cm^2	1178.41	
Sodium flow rate, Q_m	kg/sec	782.15	@ full power
Sodium flow rate, Q_V	m^3/sec	0.895	$Q_V = Q_m/\rho$ @ 322 °C
Sodium flow velocity, V_{Na}	cm/sec	759.63	$V_{Na} = Q_V/A$ @ 322 °C

Equivalent water velocity (V_{H2O}) at ambient condition (20°C) for the same nozzle pressure drop (ΔP) can be calculated as the following:

$$V_{H2O} = V_{Na}\ x\ (\rho_{Na}\ @\ T_{Na}/\rho_{H2O})^{1/2} = 710.10 \text{ cm/sec}$$

The relation between the nozzle pressure drop and the equivalent water velocity is

$$\Delta P = 0.00913\ V_{H2O}^2 = 34.17 \text{ kPa (4.96 psi) @ } V_{H2O} = 710.10 \text{ cm/sec}$$

Water flow rate through an orifice with a diameter of 1.778 mm (0.07 in.) is

$$Q_{H2O} = 0.123\ x\ \Delta P^{0.55} = 0.2966 \text{ gal/min @ } \Delta P = 34.17 \text{ kPa}$$

The desired sodium flow rate for 3-sec transit of a compact ISHM is proposed to be 13.25 cm^3/sec (0.21 gal/min). The desired water flow rate for the same pressure drop (31.1 kPa) is

$$Q_{H2O} = V_{Na}\ x\ (\rho_{Na}\ @\ T_{Na}/\rho_{H2O})^{1/2} = 12.397 \text{ cm}^3\text{/sec (0.1965 gal/min)}$$

Since Q_{H2O} is proportional to orifice area, the orifice diameter of the desired flow rate (D_0) is

$$D_0 = D \times [(Q_{H2O} \textit{ through } D_0)/(Q_{H2O} \textit{ through } D)]^{1/2} = 1.178 \text{ mm } (0.0464 \text{ in.})$$

Following the calculation, assuming same pipe diameter, the orifice diameter of a compact ISHM installed at SG inlet at 528°C is 1.278 mm (0.0503 in.). The difference of the orifice size between the inlet and outlet is negligible. For fabrication, a No. 55 drill (0.052 in.) or No. 54 drill (0.055 in.) can be used for meters located at both places.

This page intentionally left blank.

Nuclear Engineering Division
Argonne National Laboratory
9700 South Cass Avenue, Bldg. 308
Argonne, IL 60439
www.anl.gov